Technical University of Denmark

The Danish Aquifer Thermal Energy Storage Project. Demonstration Plant

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Report No. 1-4

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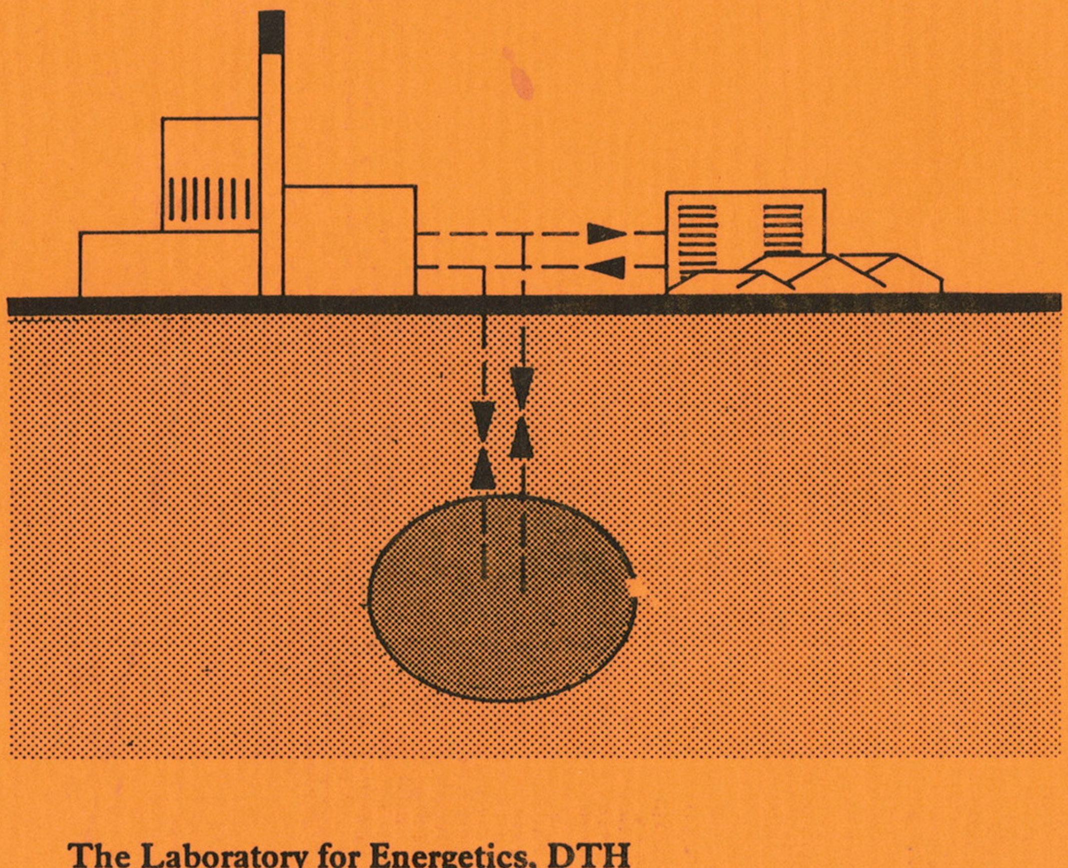
Demonstration Plant

Edited by Lotte Schleisner Ibsen and Bjørn Qvale



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The Geological Survey of Denmark
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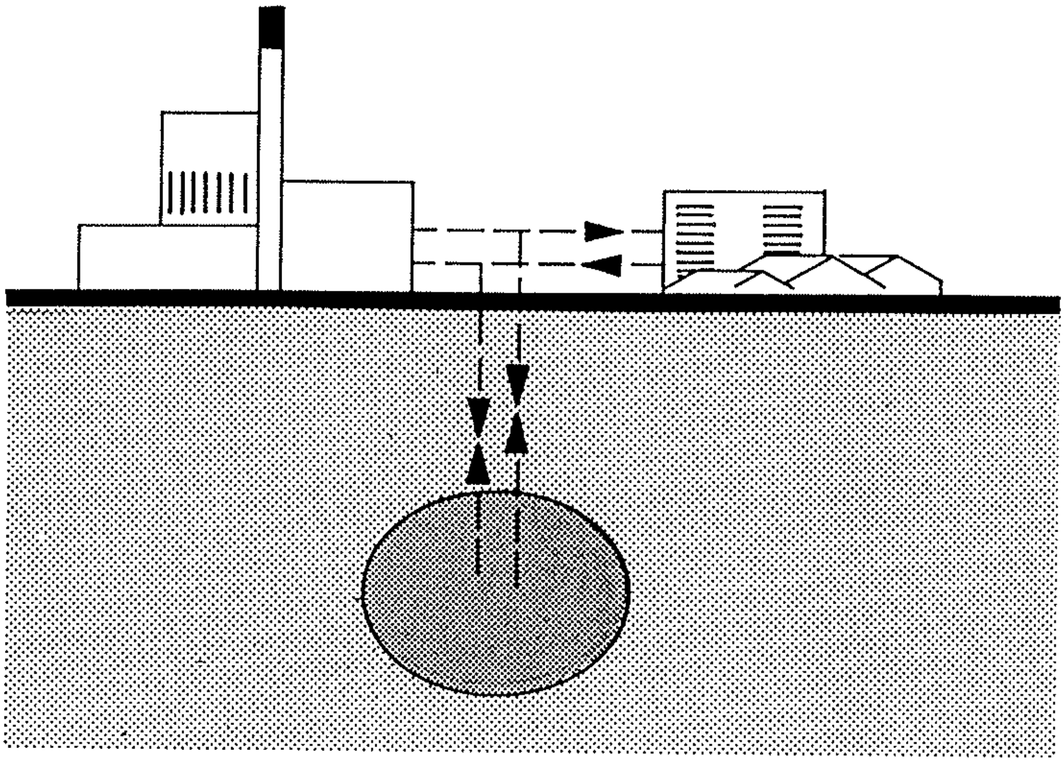

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Lotte Schleisner Ibsen and Bjørn Qvale

ABSTRACT

A part of the Danish aquifer thermal energy storage project consisted in construction of a demonstration plant. The demonstration plant was established in Hørsholm north of Copenhagen in 1982. During the years 1982-1987, altogether six charging processes have been carried out. Due to various difficulties in some years, the discharge (recovery) part of the storage cycle had to be omitted. In 1988 the demonstration plant has been closed down.

The project has been a collaboration between Risø National Laboratory, the Laboratory for Energetics at the Technical University of Denmark and the Geological Survey of Denmark.

The project has been financed by the Danish Ministry of Energy's energy research programs EM-2, EFP-80, EFP-81, EFP-82 (EM-J.No. 22633), EFP-84 (EM-J.No. 2263-411) and EFP-85 (EM-J.No. 1443/85-9).

The present report describes the original construction of the plant. Also changes in the plant which have been made to improve the plant, are described.

The six storage-recovery cycles which have been carried out during the project will be described in a subsequent report. The experiences gained and the results will be discussed in this subsequent report.

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THE DANISH AQUIFER THERMAL ENERGY STORAGE PROJECT
DEMONSTRATION PLANT

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THE DANISH AQUIFER THERMAL ENERGY STORAGE PROJECT

DEMONSTRATION PLANT

1. INTRODUCTION

The purpose of the Danish energy project is to investigate the feasibility of thermal energy storage in aquifers at high temperatures, and to make it possible to evaluate the profitability of such storage on a large scale.

The project was started in 1977 as a part of the programme for energy research of the Danish Ministry of Energy. The work is a co-operative effort between the Laboratory for Energetics of the Technical University of Denmark, The Geological Survey of Denmark, and Risø National Laboratory. The project is divided into three parallel subprojects:

1) Mathematical modelling

2) Construction of demonstration plant

3) Geological mapping of aquifers suitable for thermal energy storage in Denmark

Subprojects 1) and 3) are described in separate reports, while a description of the demonstration plant will be given here.

A part of the present report actually represents a rewriting of a report "The Danish Aquifer Thermal Energy Storage Project Demonstration Plant" from 1980 authored by Jørgen Hagelskjær. The report has been somewhat modified and updated. The subsequent chapters have been written separately by various collaborators on the project.

The coordinated collation and the final editing have been carried out by Lotte Schleisner Ibsen and Bjørn Qvale.

2. THE STORAGE CONCEPT

The search for a suitable site of the demonstration plant, resulted in the choice of a location at Kokkedal north of Copenhagen. Here the geological tests proved that conditions were acceptable, and an incineration plant with combined district heating network situated nearby, could be both a supplier and consumer of heat.

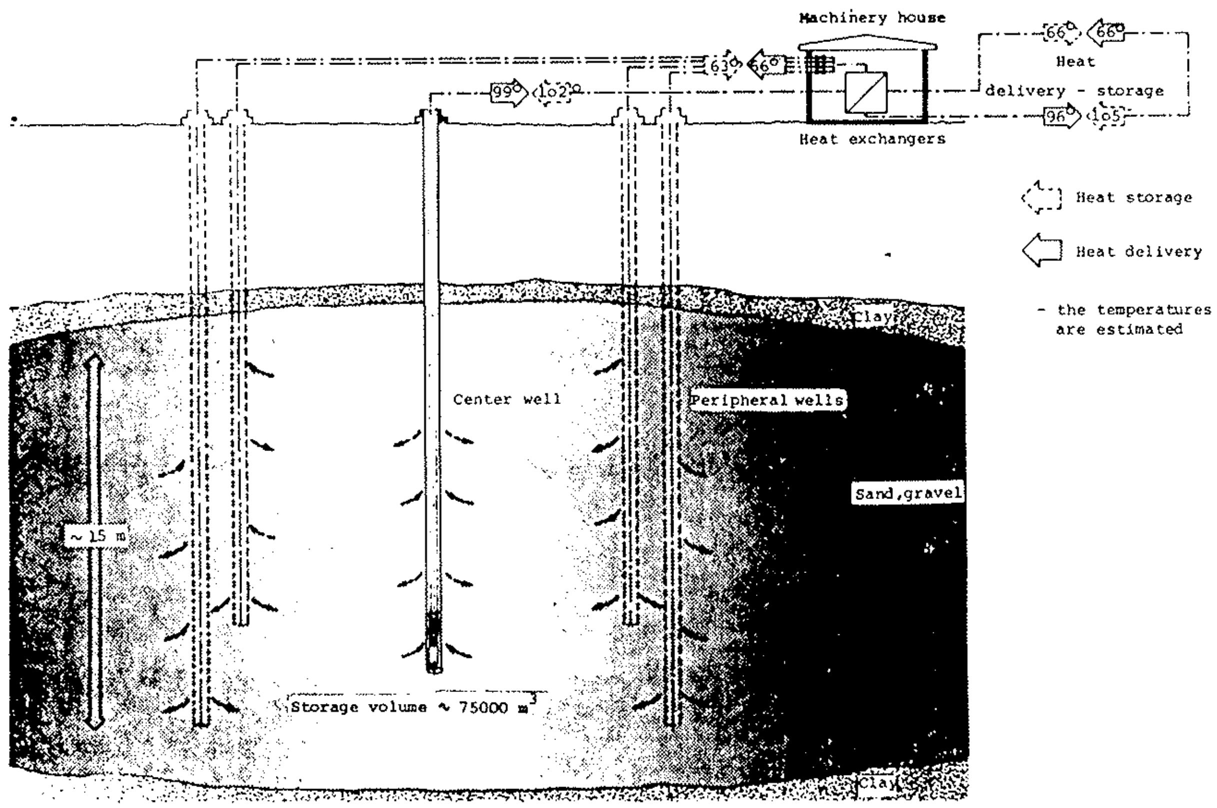


Figure 2.1 The principle of aquifer thermal energy storage

The principle of the storage concept is illustrated in Figure 2.1. A number of wells was drilled into the aquifer: One well in the centre of the storage area, and four peripheral wells at an equal distance from the central well. During storage of heat, the cold ground water was pumped from the peripheral wells to heat exchangers, where it was heated by the district heating water. From here, it was pumped to the central well and injected into the aquifer. Around the central well a hot volume with a temperature front which ideally should be vertical, was propagating concurrently with the injection. When the front reached the peripheral wells, the store was filled up.

During heat recovery, the flow direction was reversed, and the cooled water was led to the peripheral wells and reinjected at a temperature slightly above the return temperature of the district heating system. In order to insure a reasonable energy recovery, the temperature front should be prevented from tilting, thus minimising the surface area for a given volume, and thereby insuring an optimum geometry. In order to make this easier, the aquifer should be confined upwards and downwards by impermeable layers of clay. In addition, the upper layer of clay would prevent surface water from leaking down and mixing with the storage water.

3. THE BASIC DESIGN

The aquifer consisted of a porous formation with a thickness of about 15 m. The distance from the ground to the top of the formation was about 10 m and to the bottom about 25 m. The aquifer was confined upwards and downwards by layers of clay. The horizontal extension of the upper layer of clay had a limit which gave a maximum diameter of the storage area of 80 m.

The material of the aquifer was sand, with an estimated porosity of about 30% and a permeability of 10-20 Darcy.

The distance between the two layers of clay (the reservoir thickness) was not constant all over the storage area, because of a 1 to 2% sloping of the upper layer. This asymmetry had to be compensated for during the operation of the plant.

Moreover, it was expected that the potential gradient of 3 o/oo , resulting in a small regional flow of ground water, had to be compensated for, in order to keep the heat within the storage boundaries.

The ground water had a relatively high calcium hardness (about 16^{o} dH), and was treated in order to avoid scale formation in the heat exchangers and clogging of the wells due to calcium. Silica precipitation was not expected to be significant. Other sources of precipitates were not thought important at the time of the establishment of the store.

3.1 Site selection

3.1.1. Site localisation

In areas around heat sources, such as heat-power plants, where storage of hot water is a possibility, hydrogeological mapping has been carried out.

The preliminary identification of possible aquifers for heat storage was mainly done by the use of the Geological Base Data Maps which exist for all parts of Denmark. From these maps it is possible to evaluate some of the most important criteria for aquifer heat storage (see 3). Beside the sites chosen in the first place, two at Randers and one at Hørsholm, sites at Aarhus, Aalborg and Herning, which were potential for aquifer heat storage, were identified (Ref. 1).

The sites at Randers and Hørsholm were chosen near plants with surplus of heat and with extensive aquifers under confined condition. The first site at Randers was abandoned due to insufficient thickness and strength of the confining bed (Refs. 2 and 3). A second site at Randers was given up because of too high permeability and the investigations were hereafter concentrated around Hørsholm, which was later found suitable for the demonstration plant.

3.1.2. Legal aspects

No specific law or regulations exist with respect to the present type of plant. Permission therefore had to refer to law in the field of water and environment. The extraction of water for the purpose of storage was permitted according to the Water Supply Act. It was important that the same quantity of groundwater was reinjected and that no resource consumption take place.

Discharge of groundwater was permitted in accordance with the law of Environmental Protection, chapter 3, concerning groundwater protection and water supply. In the present case it was important to emphasise that the storage of hot water was going to be controlled within narrow limits because the aim of the lowest heat loss.

The permission to establish and to operate the heat storage plant involved several authorities. Referring to the Environmental Protection Act paragraph 11 an application of establishment and operation of the Hørsholm plant was sent to the National Agency of Environmental Protection. The application contained information of the plant, such as a description of the plant, the groundwater conditions, the environmental aspects, the number and configuration of wells, and temperature levels of the water that should be processed. The permission from Ministry of The Environment was given on condition of complete chemical and bacteriological analyses before and during the storage.

The principal permission for site investigations and establishment of the plant was given by Hørsholm Kommune. Hovedstadsrådet gave the permission for groundwater extraction. Gentofte Water Supply gave the permission for extraction of water provided that it did not interfere with their own production of water from the limestone aquifer in wells located 1-2 kilometres from the Hørsholm Plant.

3.1.3. Environmental aspects

The most important environmental requirement was that no drinking water supply should be affected. The nearest water supply wells, 1,5 km away from the plant, utilised the limestone aquifer, which was separated from the heat storage aquifer by a formation of till. Therefore, the hydraulic connection between the heat storage aquifer of meltwater sand and the limestone aquifer should be very limited. A prime requirement to the location of the plant was that it should not interfere with the normal water recovery. In the present case the nearest catchment area was situated about 1.5 km away.

Based on this, the environmental authorities permitted the storage plant to operate under the following two conditions:

1) that no chemicals should be added to the ground water except a small amount of hydrochloric acid required to prevent scaling and clogging, and

2) that a frequent monitoring of the flora of bacteria should be kept by taking water samples. These samples should be examined with respect to both bacteria and toxins.

To avoid precipitation of $CaCO_3$ on undesirable locations in the system, water treatment with HCl was incorporated. The chemical contamination of the surroundings was expected to be insignificant since the water was circulating in a closed system without direct contact with the atmosphere.

Water samples should be taken during storage in order to detect any bacteriological changes that might arise. However, anaerobic conditions, limited amount of organic material and large temperature fluctuations were conditions which were unfavourable for bacteria growth.

A specific problem in connection with the Hørsholm plant was that the selected area is protected by law. In connection with the permission it was, therefore, required that the pump wells should be buried and buildings above the ground should have a discrete appearance. Besides, it should be possible to dismount the plant when the experiment was completed.

3.1.4. Site investigations

Site investigations refer to detailed investigations in a limited area of a couple of square kilometres around the heat source.

The Base Data Map (1514 II Hillerød) showed an aquifer more than 20 m thick in several boreholes in or around the area investigated, but gave only a vague indication of an upper confining bed.

Geoelectrical survey

During the winter 1979 geoelectrical soundings were carried out in the investigation area. East of the railroad all the soundings (5) indicated a bed of sand with a thickness of 15-35 m (Ref. 4). Three (3) soundings indicated an upper clay bed of 5-10 m, the other soundings did not. Therefore, the next step was to verify the geoelectrical predictions by drilling.

Drilling programme

Five 8 inch test wells (R1-R5), shown in Fig. 3.1, were drilled to depths of 25-40 m. All wells penetrated an aquifer of fine to medium grained meltwater sand with thickness of 15-25 m.

Boreholes R1 and R2 in the north-western part of the area had only very thin clay beds less than 0,5 m and R5 had about 3 m of clay above the aquifer of meltwater sand. Furthermore, the conditions in the aquifer were non-artesian, thus excluding the area around these three wells. In R3 and R4, however, confining clay beds of around 5 m existed above the aquifer, and consequently further investigations were concentrated here.

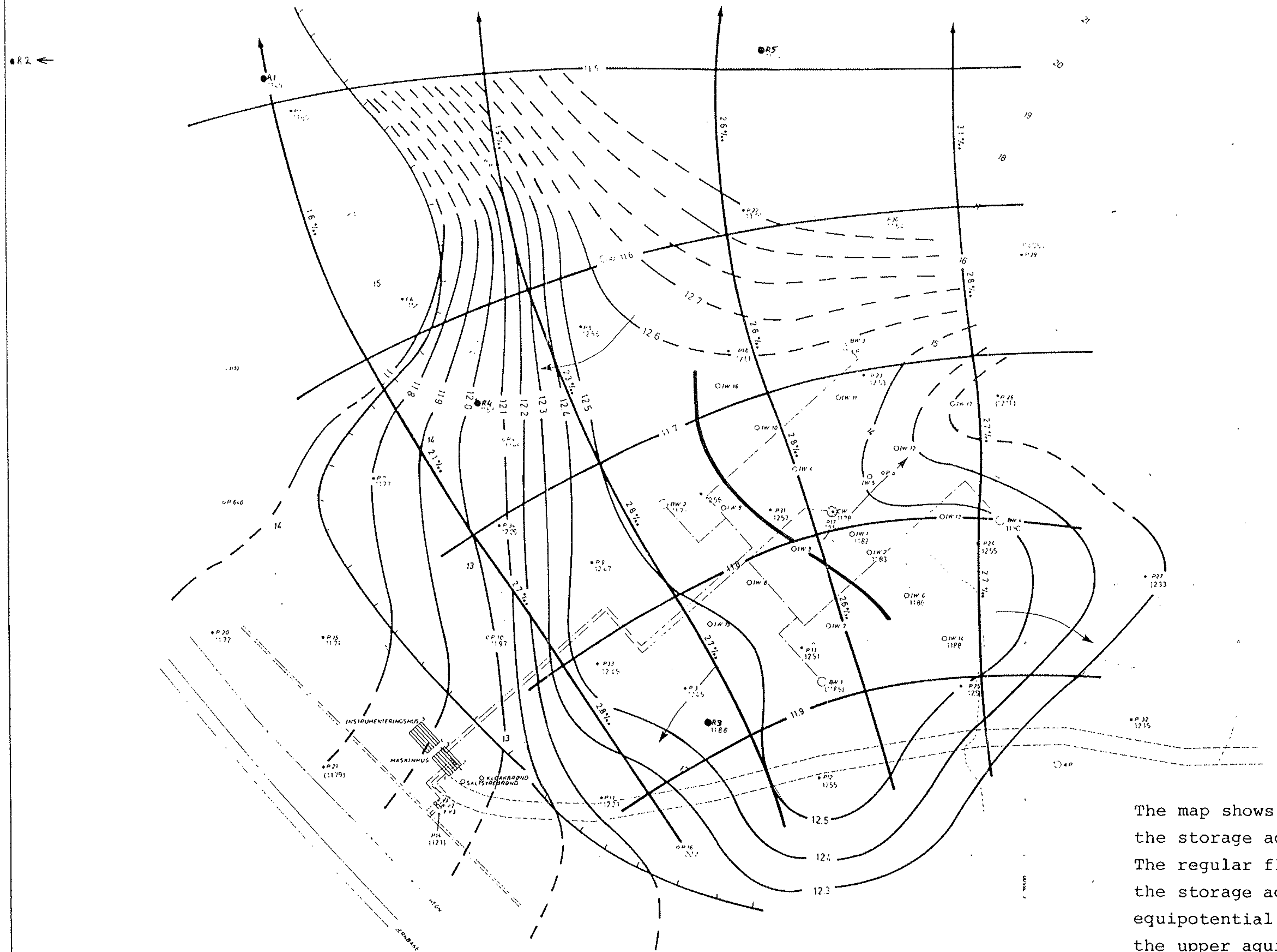
Pumping test

The hydraulic properties of the aquifer were determined by several pumping tests in the investigation wells. Based on these tests the average transmissivities of $T = 1,2 \times 10^{-3}$ m^2/sec and a coefficient of storage $S = 5 \times 10^{-4}$ were obtained. Thus the criteria of low to medium hydraulic conductivity should be fulfilled. During the pumping tests water levels were measured both in the test wells and in several piezometers screened in an upper aquifer. It was not possible to estimate leakages that might occur through the confining bed due to the complexity of the aquifer which included both artesian and non-artesian conditions (see Section 3.3.1).

Mapping of the confining bed

From the geology of the investigation wells it was obvious that the confining bed was sufficiently thick (5 m) only in R3 and R4, and that the confining bed almost disappeared towards north and north-west around R1, R2 and R5. Therefore, decisions were made to pursue the investigation of the confining bed around R3 and R4. Thirtyfive (35) shallow boreholes with maximum depth of 6 m were drilled with a tractor-mounted snail. A 1 inch PVC tube was installed in each borehole, which was screened in the upper aquifer or at the bottom of the borehole. The borehole samples indicated that the confining bed probably ceased towards north-west and became very sandy to the west along the railroad. A new pumping test was performed including intensive draw-down tests that were measured by piezometers. The tests showed relatively good vertical hydraulic conductivity to the west along the railroad and poor vertical hydraulic conductivity towards the north-east. However, a quantitative determination of the vertical permeability was still not possible due to the complex aquifer conditions.

Fig. 3.1 shows groundwater contour lines of the storage aquifer and of the upper aquifer. The boreholes P1-P35 are also indicated. Generally the water table of the upper aquifer is above the table of the storage aquifer. Towards the west and the south-west, however, the distance between the two levels becomes smaller and smaller and coincide in the unconfined part of the storage aquifer, thus indicating the boundary of the confining bed (see 3.3.1 and 3.3.2).



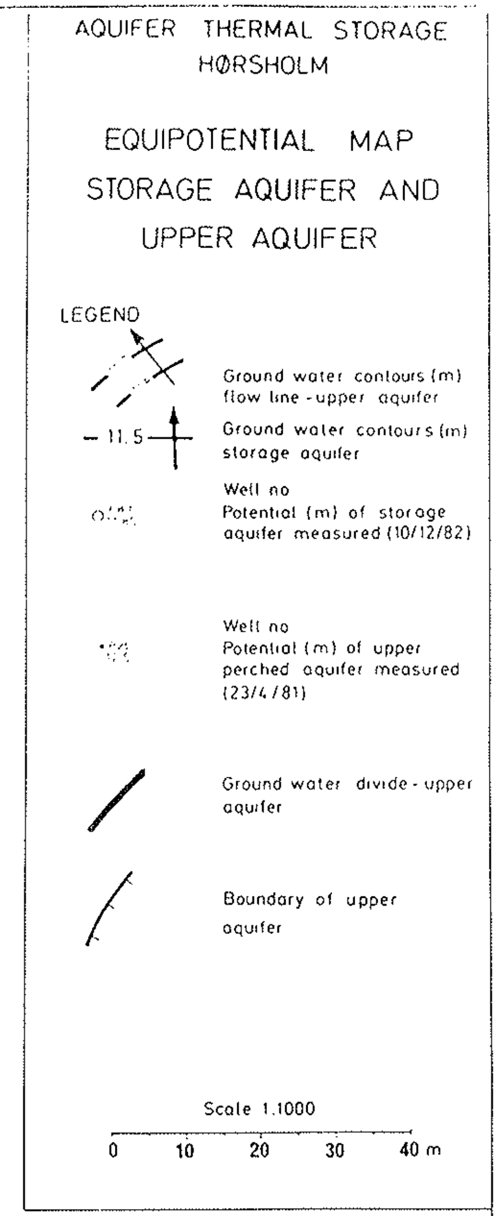
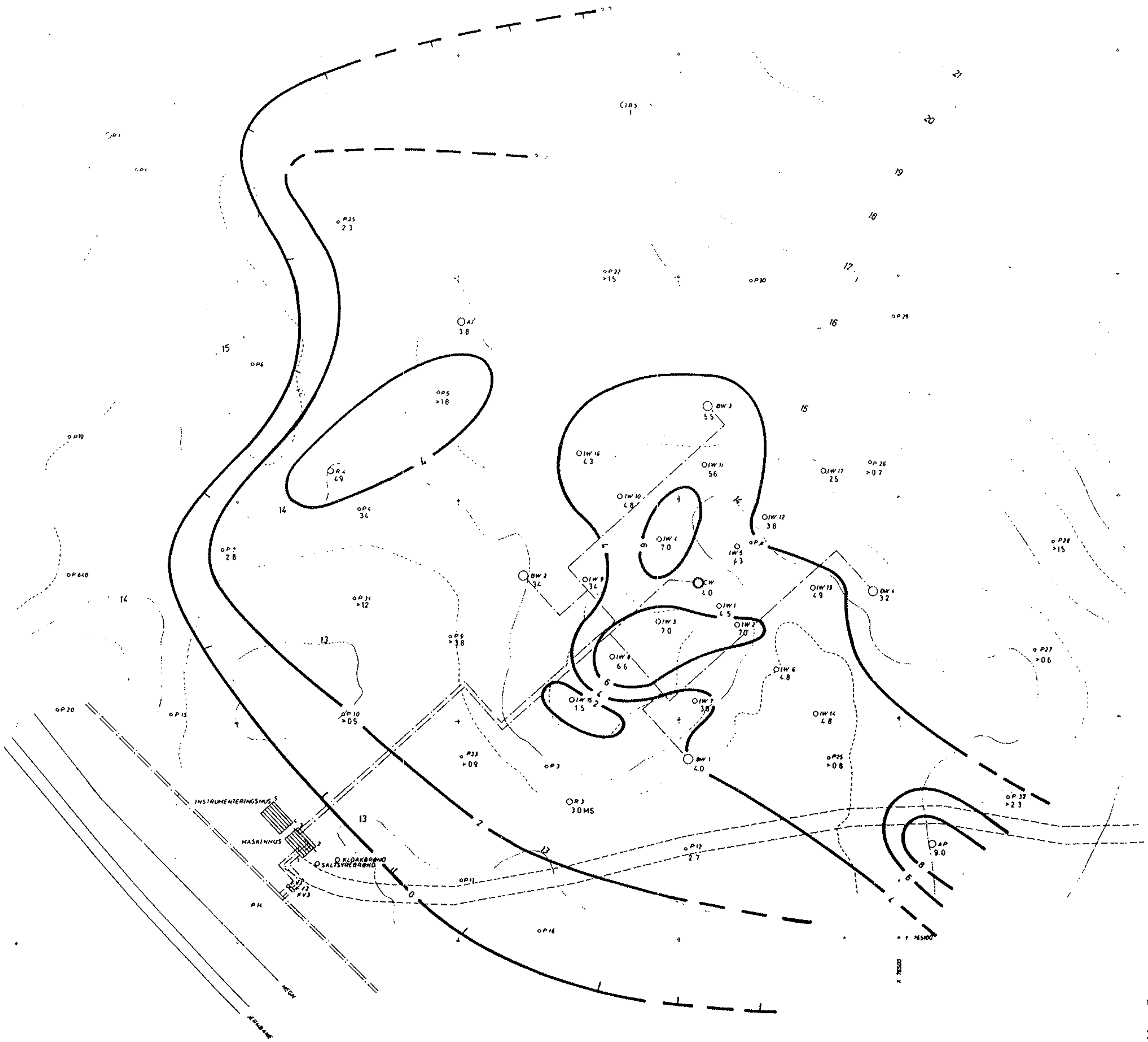


Fig. 3.1 Groundwater contour lines of the storage aquifer and of the upper aquifer

The map shows equipotential lines of both the storage aquifer and the upper aquifer. The regular flow net (thick lines) represents the storage aquifer, while the more irregular equipotential lines (thinner lines) represents the upper aquifer. In the storage area, the head of the upper aquifer is about 0.7 m higher than the storage aquifer. The difference diminishes towards the West as both aquifers coinside into one water table aquifer.



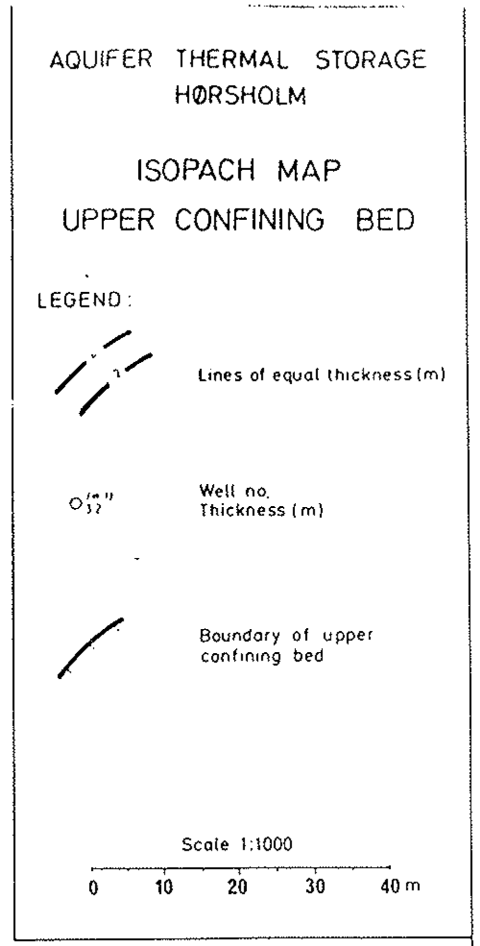


Fig. 3.2 Boundary of the confining bed

The isopach map shows the thickness of the upper confining bed. Within the storage area the thickness is generally more than 4 meters. To the Southwest, West and Northwest the confining bed becomes thinner and finally cease.

In order to analyse the connection between the two reservoirs and the distribution and character of the confining bed further, an evaluation of the fluctuations both periodically during a long period and in connection with pumping test have been made (see 3.3.3). If the fluctuations of the two aquifers were equal it was believed to indicate that the confining bed was not an efficient hydraulic barrier. The boundary of the confining bed is drawn on Figure 3.2.

3.2. Geology

The general geology around the investigation area can be read from the Geological Basic Data Map 1514 II Hillerød. Around Kokkedal the prequaternary surface lies between 25 and 30 m b.s.1. and consists of limestone (Kalksandskalk). The quaternary deposits mainly consist of meltwater sand and clayey till with a total thickness of 30-45 m.

The following geological description is primarily based on data from boreholes, which were drilled in connection with the project. The numerous closely spaced boreholes with samples taken each meter makes it possible to describe even a thin bed and to map the spatial distribution of the formation. The geology of the area is illustrated in a block diagram, where the major part of the deep wells are shown, (Figure 3.3). Detailed geological description and gamma logs of CW1, PW1, PW2, PW3 and PW4 are shown in Figs. 3.4, 3.5, 3.6, 3.7 and 3.8.

3.2.1 Stratigraphy

Lower till

From the block diagram (Figure 3.3) it is obvious that the lower part of all the deep boreholes intersect till and/or meltwater clay. Both the till and the meltwater clay are firm and compact, silty, olivegrey with a bluish tinge. Foraminiferal analysis (P. Konradi, DGU) revealed that both sediment types belong to a formation called "Græsted Clay". From the nature and distribution of the Græsted Clay it is almost evident that it constitutes a nearly impermeable lower boundary of the heat storage aquifer.

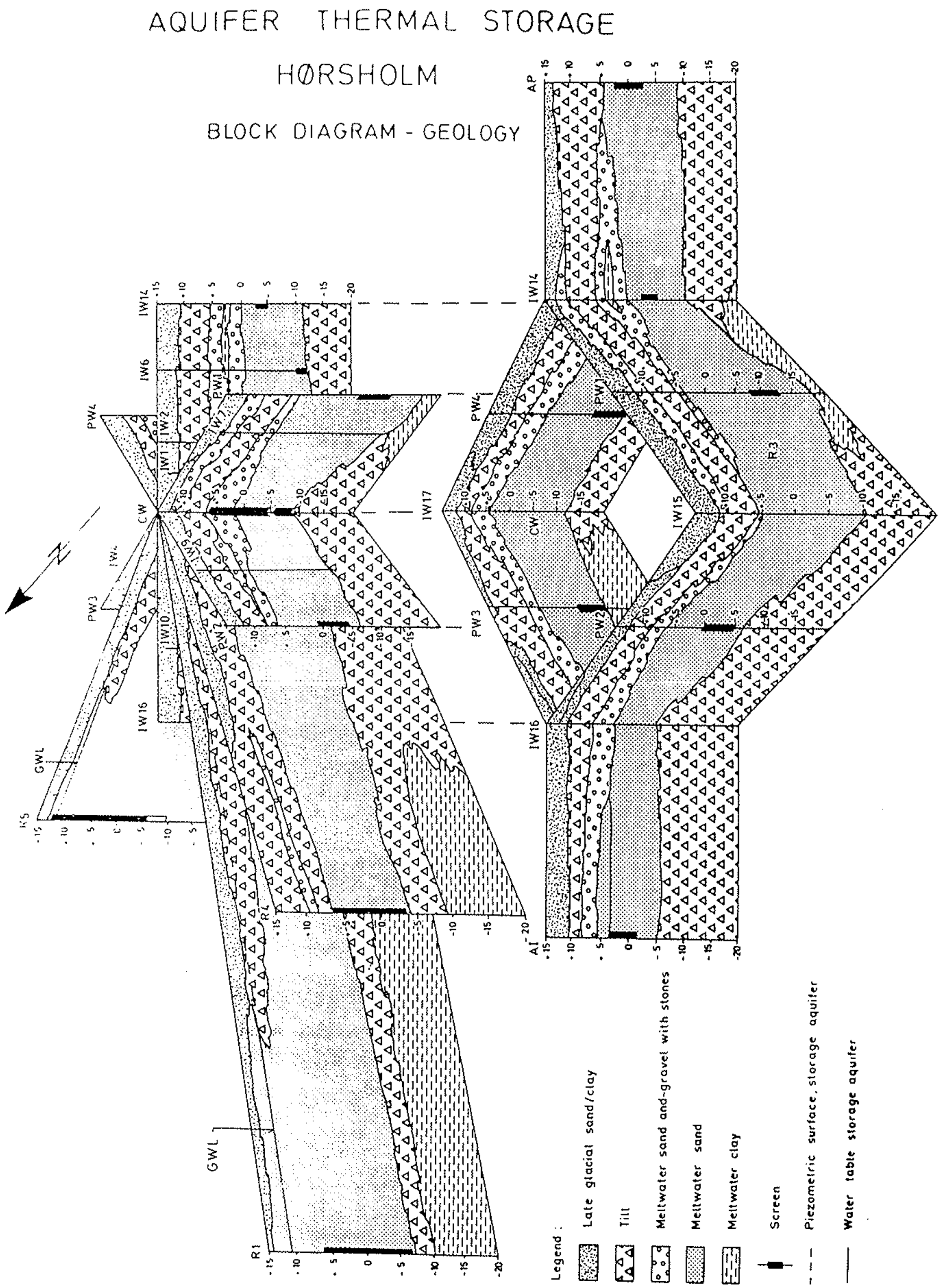


Fig. 3.3 Geological block diagram

The geological block diagram illustrates an aquifer of meltwatersand (storage aquifer), which is upwards and downwards limited by clay beds. The upper clay bed (confining bed) cease towards North and West.

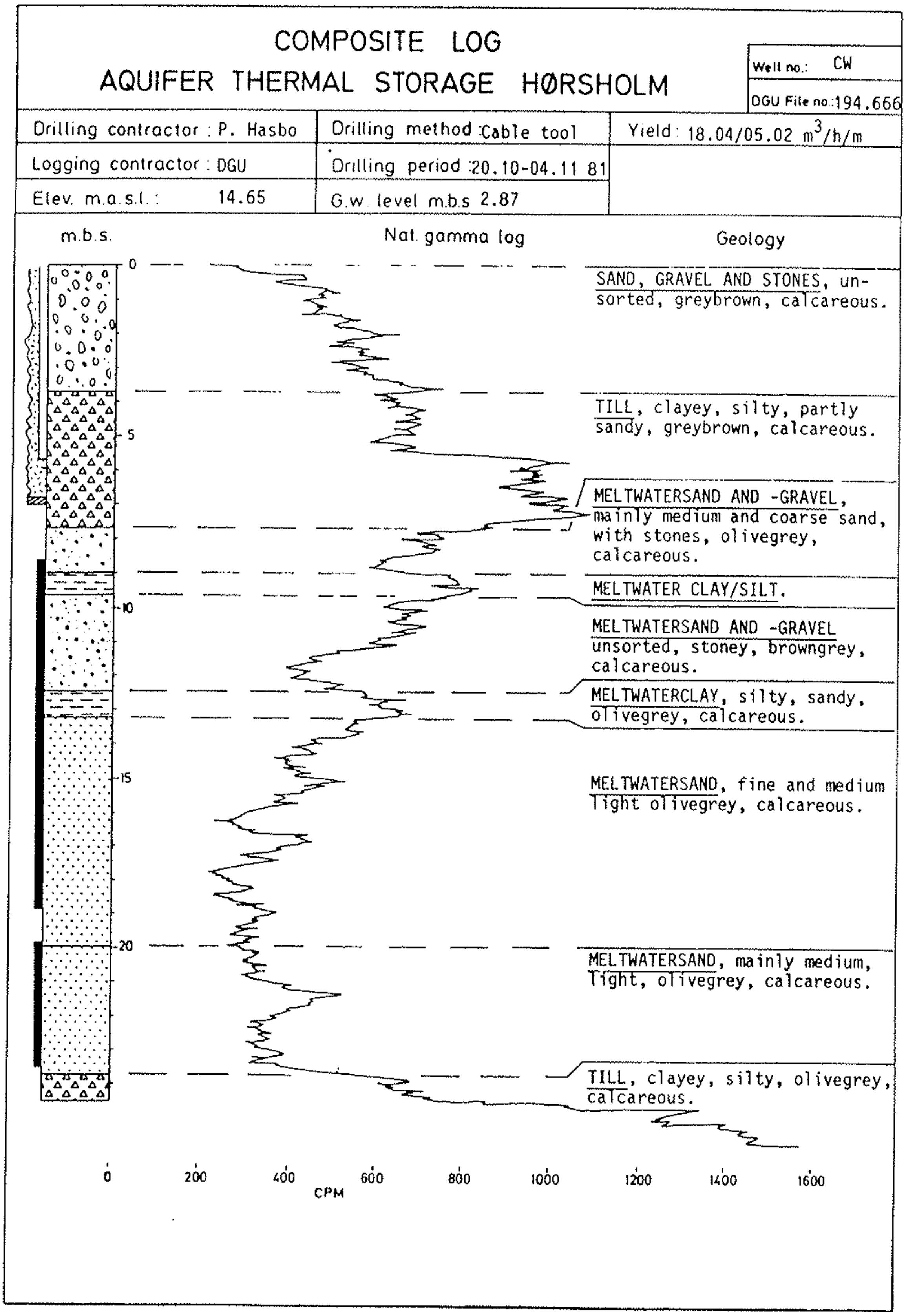


Fig. 3.4 Detailed geological description and gammalog of CW 1

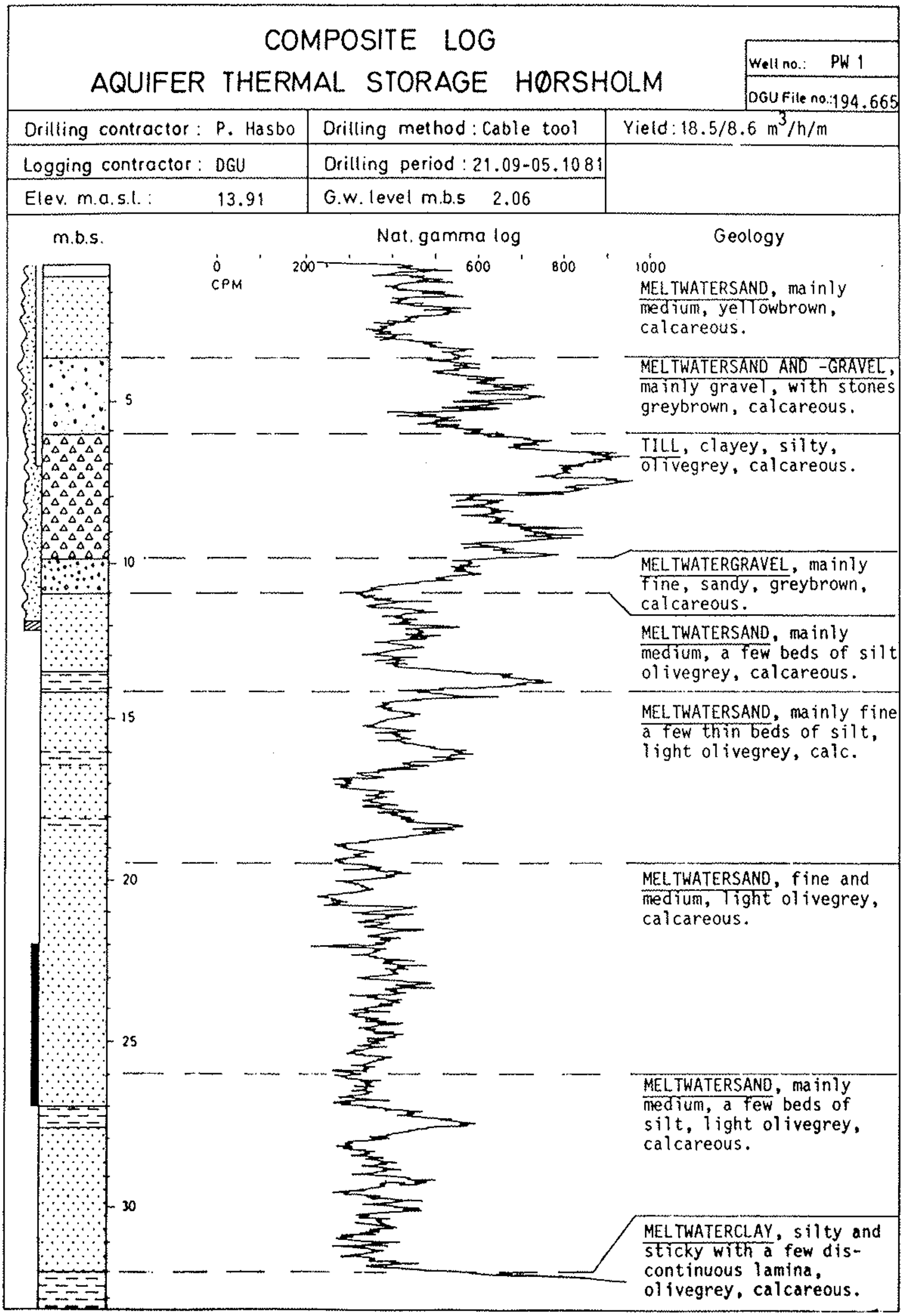


Fig. 3.5 Detailed geological description and gammalog of PW 1

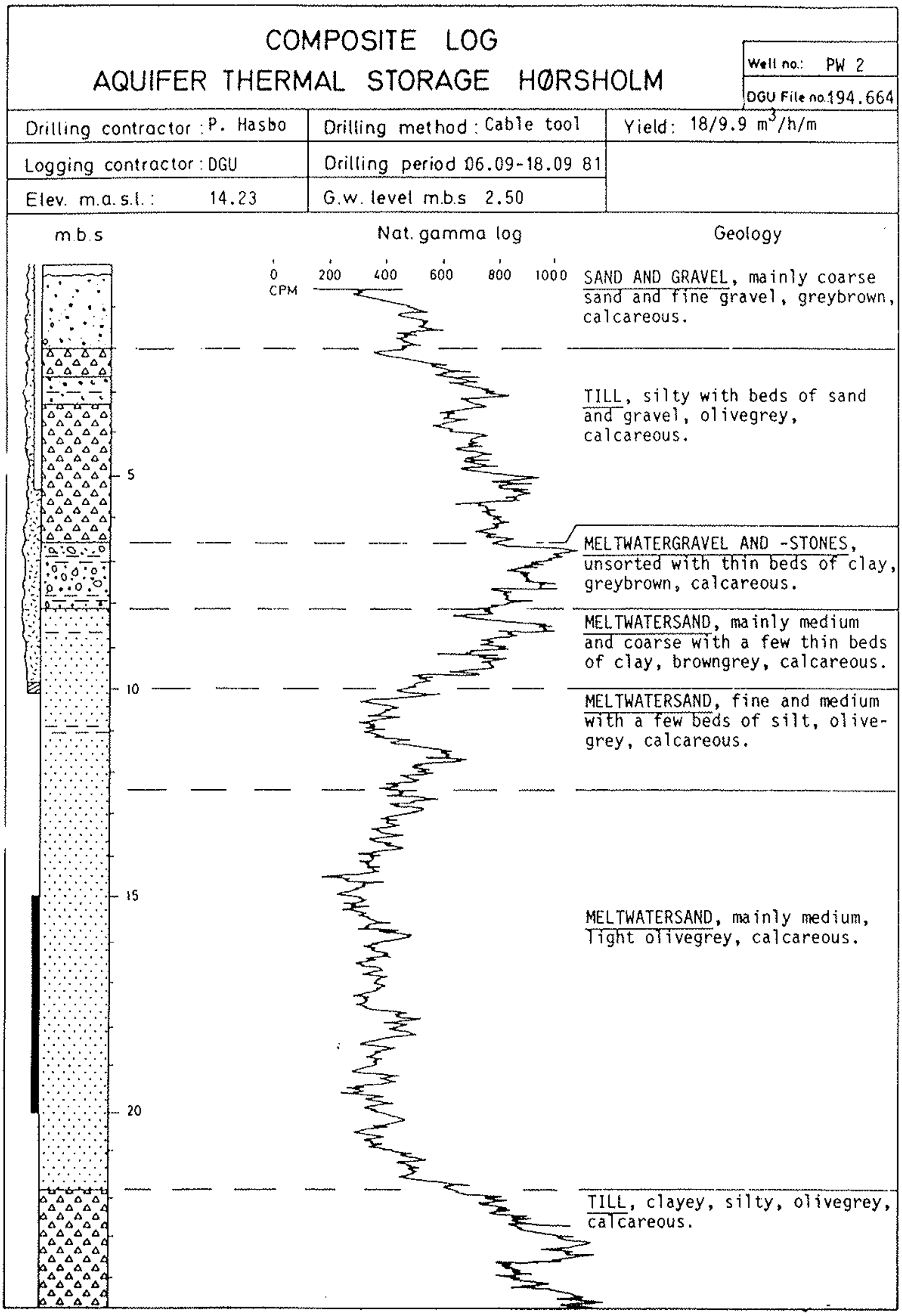


Fig. 3.6 Detailed geological description and gammalog of PW 2

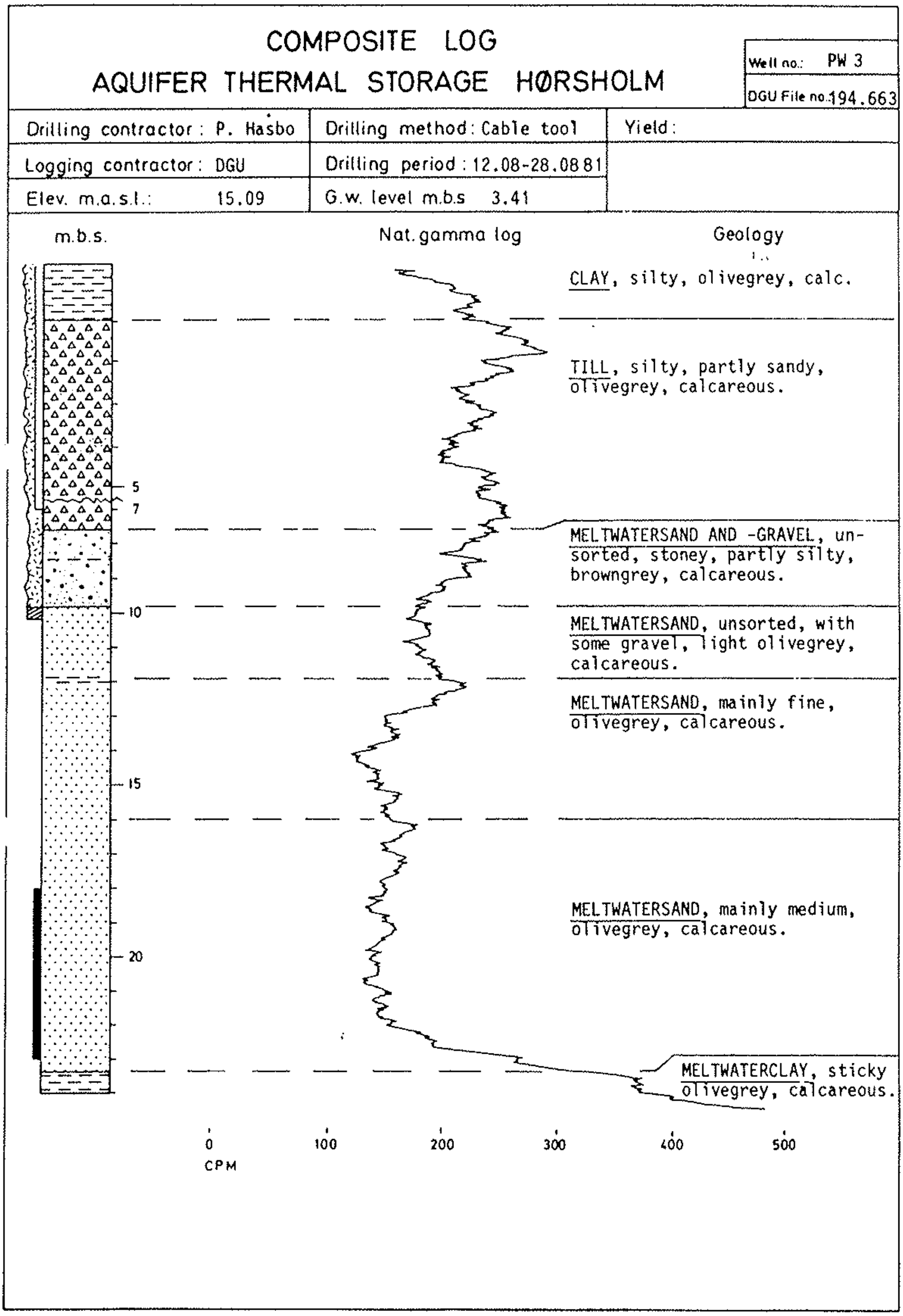


Fig. 3.7 Detailed geological description and gammalog of PW 3

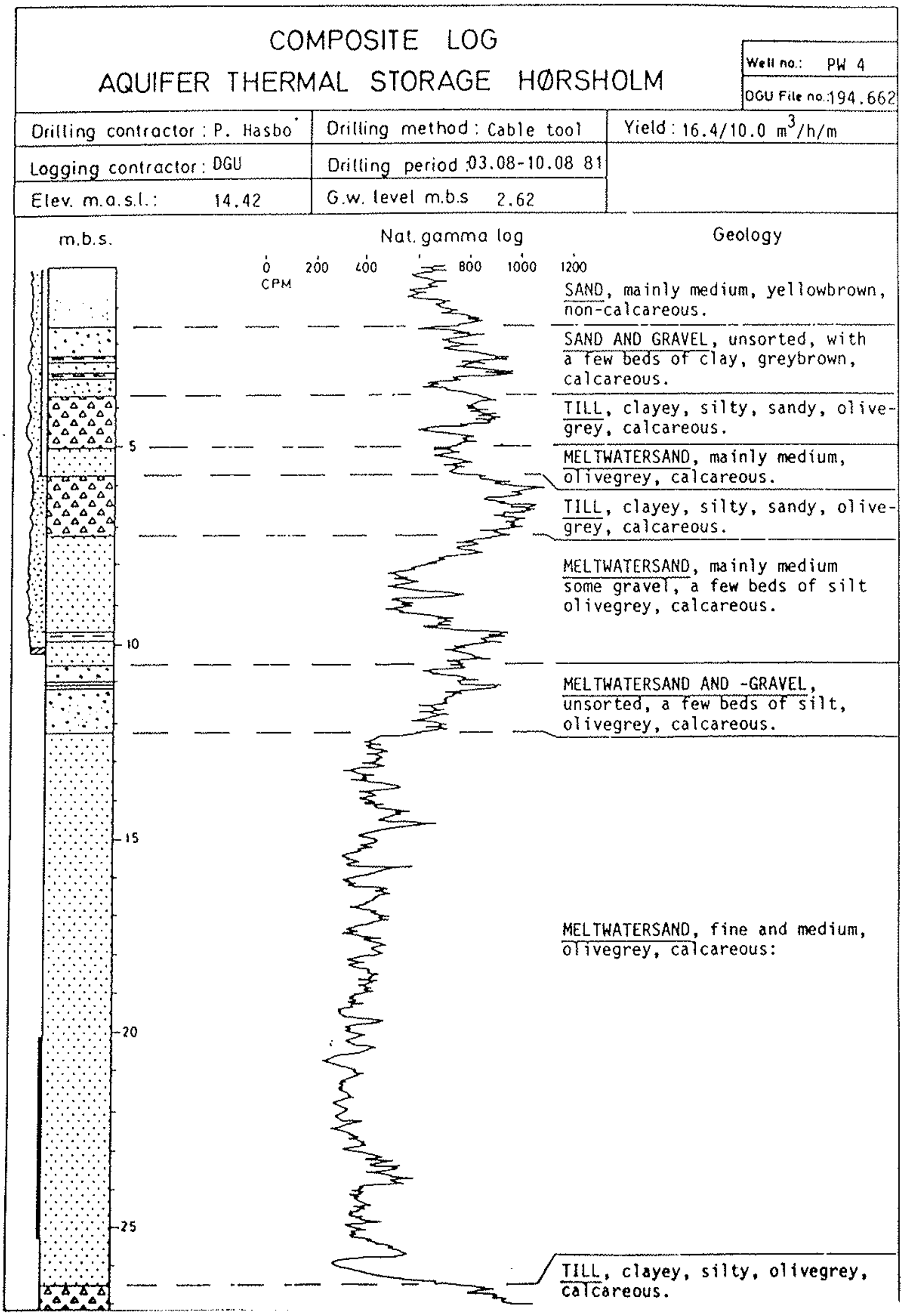


Fig. 3.8 Detailed geological description and gammalog of PW 4

Finegrained meltwater sand (storage aquifer)

Above the Græsted Clay is deposit a formation of fine-grained meltwater sand, which is the storage aquifer. The grainsize distribution of the sand appears from the numerous grainsize distribution curves - totalling 90. They show that the sand predominantly is fine grained and well sorted with coefficient of sorting ($U = {}^{d60}/_{d10}$) between 1,1 and 1,8, but on average 1,3. Further, it is characteristic, that the grain size increases downwards - fine grained at the top and medium grained towards the bottom. The clay/silt content of the samples varies between 0 and 8% but is generally between 1 and 3%. It is assumed that the clay/silt content of the sediments is higher than that of the samples because the clay/silt may be washed out during the drilling operations.

Heterogeneous glacial sediments

Above the fine-grained meltwater sand follows a heterogeneous zone, which has a thickness of about 5 m in the major part of the storage area. Generally, the zone consists of sand and gravel changing with thin beds (< 1 m) of silt and clay, (Figure 3.9). The samples often consist of sand and gravel mixed with a considerable content of clay and silt. In the centre well (CW1), for example, the coefficient of sorting from samples at depth of 8.3 - 11 m lies between 2.6 and 4.0, which means that the samples are poorly sorted. On the other hand, some parts of the zone consists of well sorted sand with an insignificant amount of silt and clay.

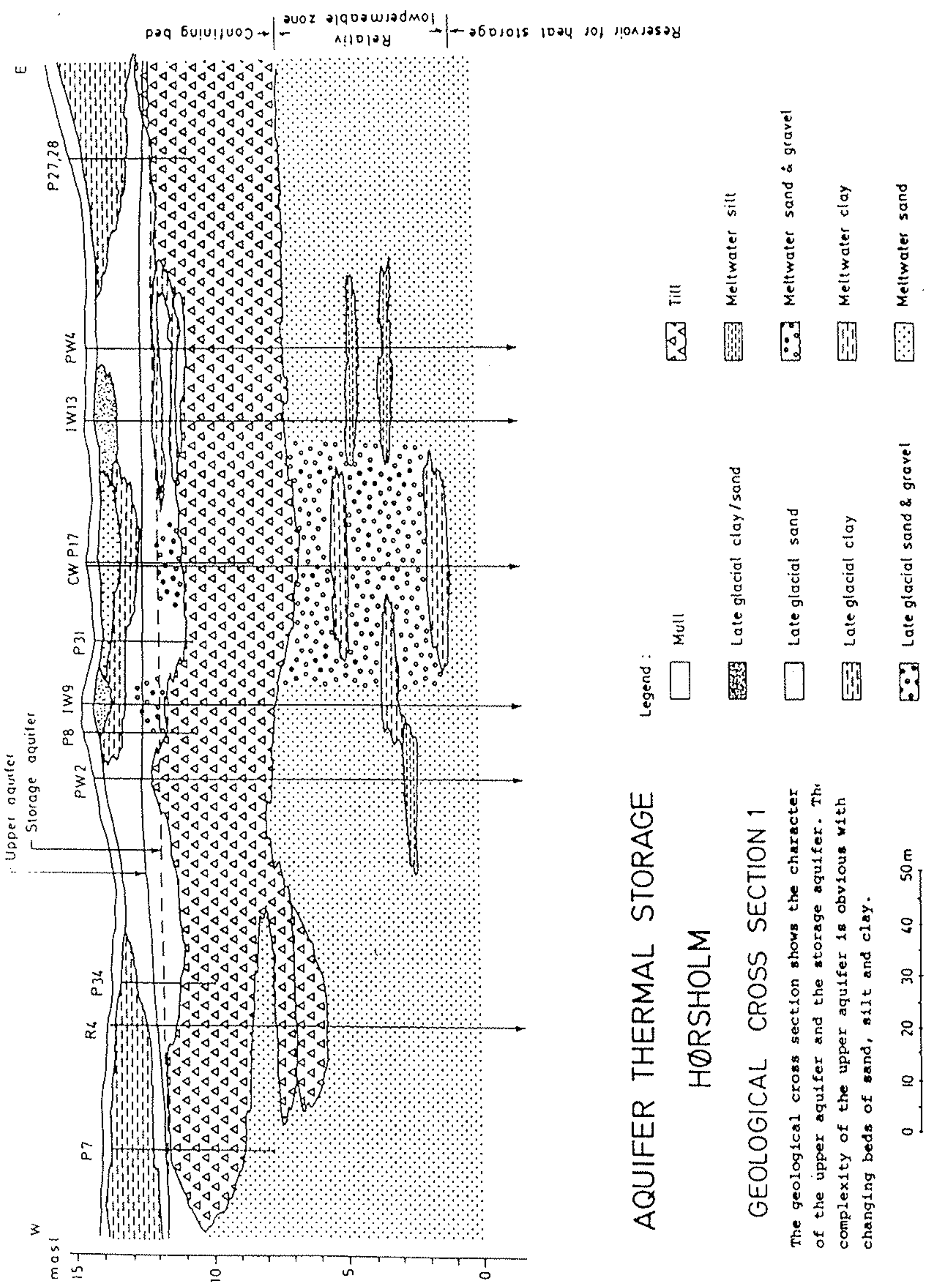


Fig. 3.9 Geological cross section WE

Upper till

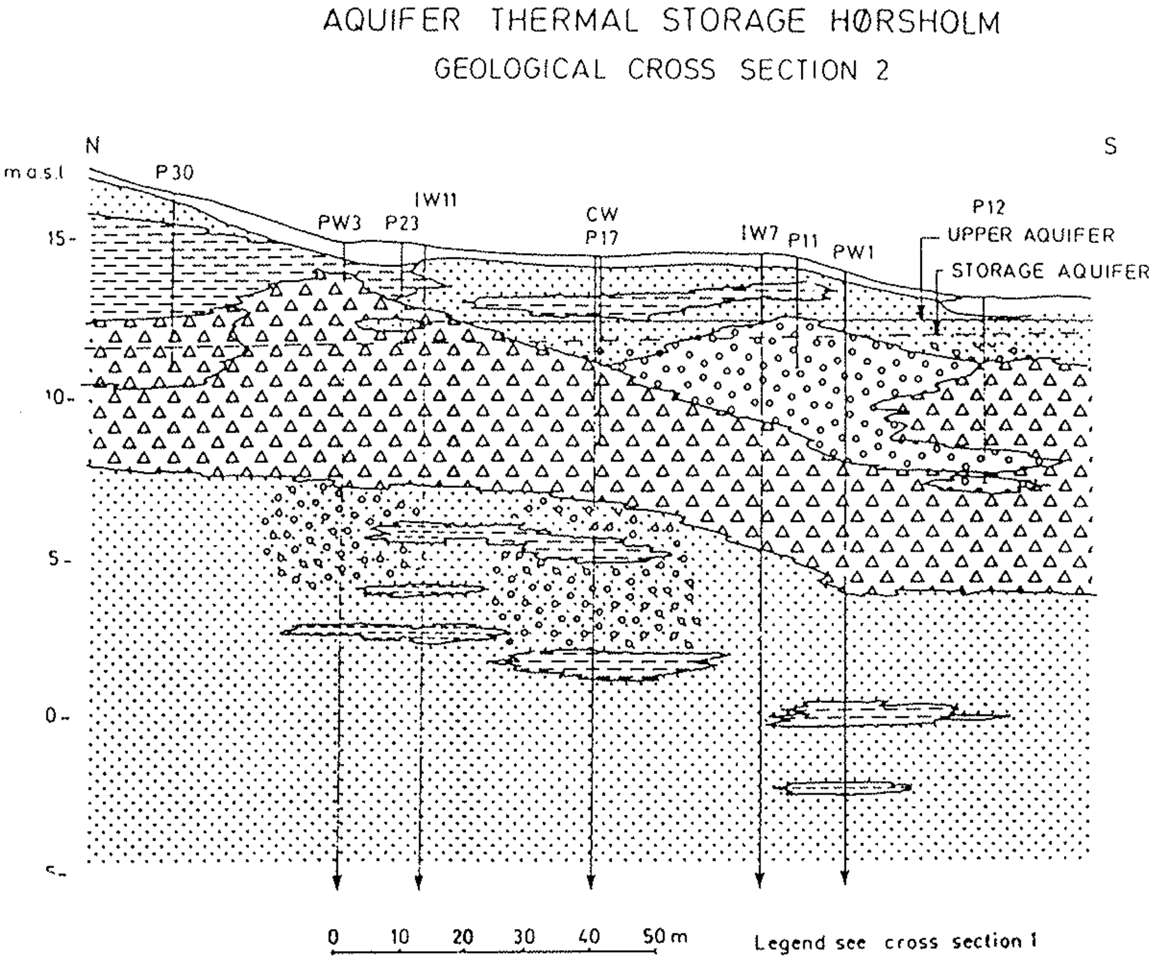
The heterogeneous zone is followed by the upper till, which is the confining bed of the storage aquifer. The till is silty and sandy and less compact and firm than the lower till. The thickness and the distribution of the confining bed is shown on Figure 3.2. It is obvious that the till exists in all boreholes within the storage area with thickness varying from 1,5 to 7 m. The thickness is 4-6 m in the central part of the storage area from where it decreases in all directions. At IW 15 the thickness is only 1,5 m, which is believed to be a minimum within the storage area. The thickness and distribution of the confining bed is determined by borehole information and by results from pumping tests.

Late glacial sediments

The surface near deposits between the mull and the upper till are described as late glacial sediments. Their thicknesses vary between 2 and 5 m. The late glacial sediments consist of sand and gravel changing to irregular beds of clay and silt (cross section 1 and 2, Fig. 3.9 and 3.10). The beds of sand and gravel have the same character as the sand- and gravel beds in the heterogeneous zone. The late glacial deposits make up the upper aquifer, which has an irregular spatial shape. The clay beds often contains small remnants of plants and exhibit flow structures, that are the main criteria justifying the classification as late glacial deposits.

3.2.2. Geological setting and environment

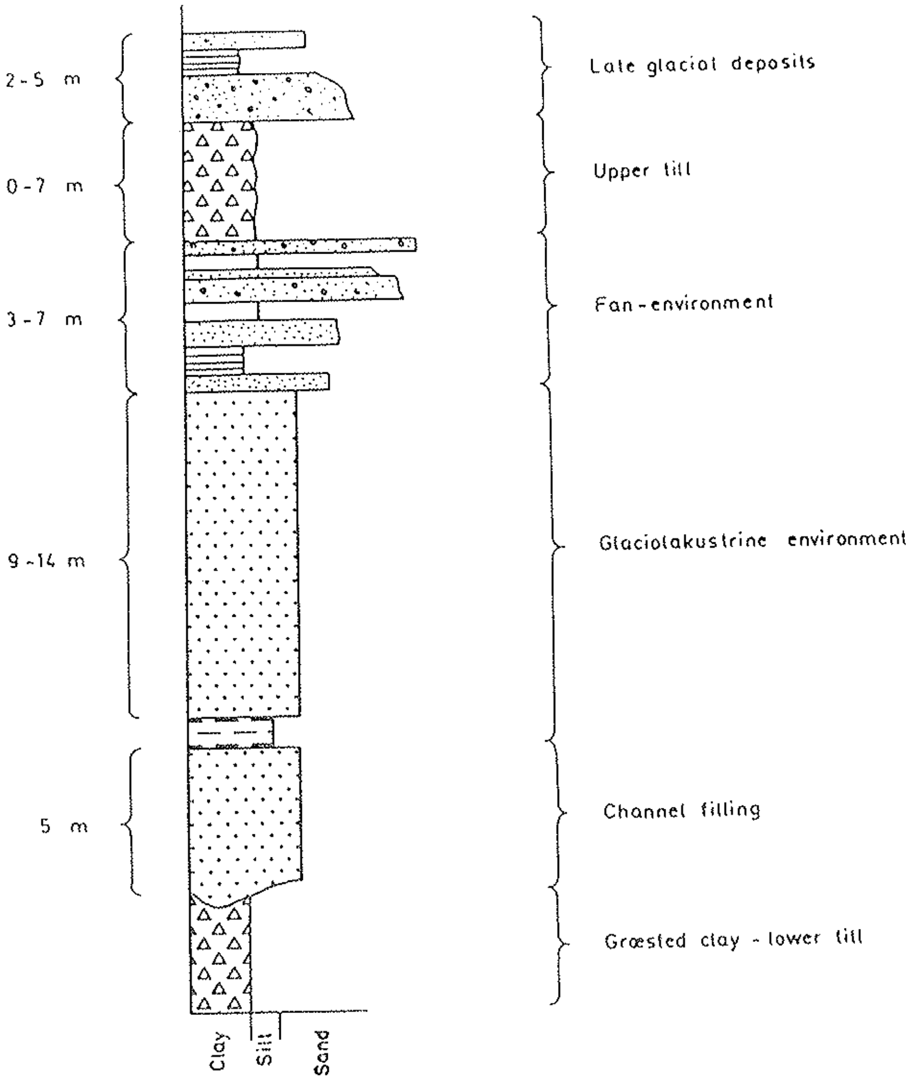
The interpretation of the geological setting and environment (Figure 3.11) is only based on borehole samples and gamma logs. The lower till or the Græsted Clay, is probably the till that Rørdam (1983) described as lower till. It is according to foraminiferal analysis a marine glacial deposit probably originated from an advance of ice from the north (Ref. 5).



The character of the two aquifers is similar to cross section 1. Notice that the upper aquifer becomes more clayey towards the North.

Fig. 3.10 Geological cross section NS

The meltwater sediments in the storage aquifer is dominated by deposits of fine sand. In the southern part of the storage area is an elongated north-south directed depression in the Græsted Clay which is filled with fine to medium grained sand. This depression is interpreted as an erosion channel in the Græsted Clay, which later is filled with meltwater sand. The channel sand is slightly more coarse grained than the sand above and is separated from that by a thin bed of silt. Above the silt bed follows a sequence of well sorted progressively finer sand with a thickness of 9-14 m. This sequence, interpreted as a lacustrine deposit (deposit in a lake), probably originated as an ice-dammed lake.



An interpretation of the different sedimentological environments accompaigns the sedimentological profile. The storage aquifer is a combination of a glaciolacrustrine environment, a channel filling, and a fan environment.

Fig. 3.11 Idealized sedimentological profile

The heterogeneous zone is characterised by changing beds of unsorted sand and gravel with a significant content of silt/clay. Further upwards some beds of silt and clay are present. This zone is interpreted as a fan-environment. The few well sorted beds of sand in the sequence is interpreted as channel fillings in the fan-environment. The upper till has a thickness of 5 m and contain a considerable amount of sand. It is probably the till Rørdam (1983) (Ref. 6), described as upper till.

The late glacial deposits is formed after the melting of the ice. In some of the clay deposits small plant remnants and flow structures are observed, which indicate that the upper beds have been mobile in the late glacial period.

The geological setting may be summarised as follows:

1) Ice advanced from the north and melted, thereby forming the Græsted clay. During the melting, erosion of a channel in the Græsted clay took place and was filled in with meltwater sand.

2) Lacustrine fine sand was deposited.

3) A fan-environment was formed near the ice front.

4) New ice advanced and the upper till was deposited.

5) Late glacial sediments were formed by flow-processes.

3.3 Hydrogeology

3.3.1 Storage aquifer

The storage aquifer lies between 5 m a.s.l. and 20 m b.s.l. and is both upwards and downwards limited by clay beds. The aquifer is under artesian conditions within the storage area. The piezometric surface lies between 11,7 and 11,9 m a.s.l. corresponding to 1-4 m below the surface.

From the Base Data Map 1514 II Hillerød and the block diagram Figure 3.3 it is obvious, that the storage aquifer extends further than the area of investigation - at least 1 km in all directions.

Thickness

The thickness of the storage aquifer is shown on the isopach map Figure 3.12. The thickness of the aquifer within the storage area varies between 9 and 20 m. The maximum thicknesses occur around the wells PW1, IW7 and IW3, due to the depression (erosional channel) in the lower till (6.2). In the storage area away from the channel the thicknesses are from 9 to 14 m. Outside the storage area the thickness increases towards the north and reaches 25 m at R5.

The boundary between the lower aquifer and the lower till is everywhere sharp. Contrary to this the upper boundary of the aquifer is irregular. The reason is that the heterogeneous zone in some parts consists of permeable well-sorted sediments of sand and in other parts consists of low permeable beds, which are very different from the storage aquifer.

Piezometric surface

The piezometric surface under natural flow based on water level measurements of 10.12.1982 is shown on Figure 3.1. The map is drawn with an equidistance of 10 cm. The groundwater flow is towards NNW in the southern part of the investigation area and turns to straight north in the northern part. The equipotential lines varies less than half a meter within the map corresponding to 11,5-11,9 m a.s.l.. Consequently the hydraulic gradients are small, 2,6-2,8 o/oo in the storage area, decreasing to 1,6 o/oo in the north-western part of the investigation area. The smooth equipotential lines and the small variations in the hydraulic gradient indicate a relatively homogeneous reservoir, which supports the geological description of the storage aquifer.

Permeability (hydraulic conductivity)

Two different methods have been used to determine the permeability distribution in the storage aquifer:

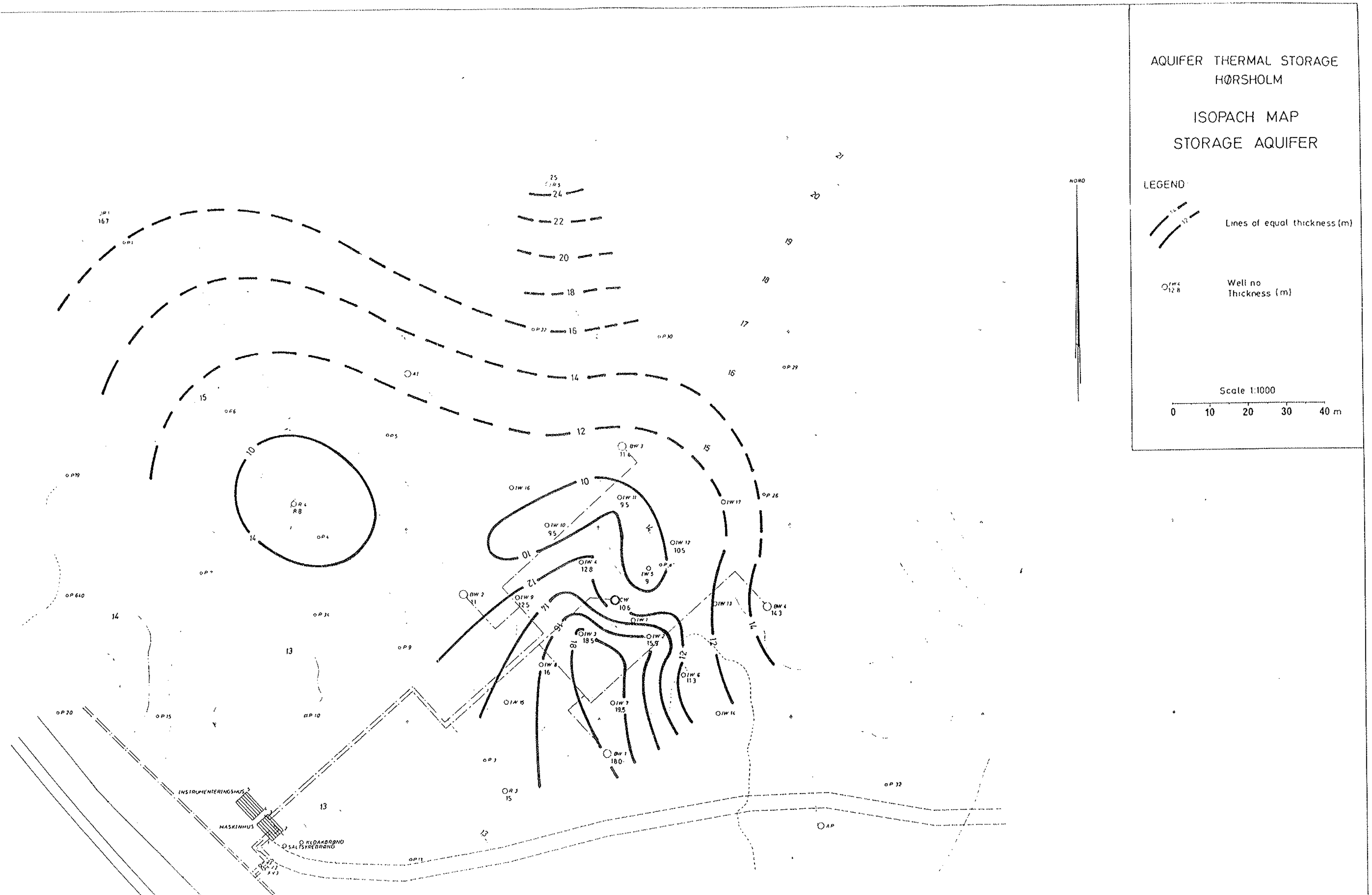


Fig. 3.12 Isopach map

The isopach map shows the thickness of the storage aquifer. In the storage area the thickness is generally between 10 and 18 m, thickest towards the South around PW 1. Outside the storage area the thickness increases towards the North and reaches 25 m at R5.

1) Granulometric method
2) Flow log

Strictly speaking the granulometric method is a method for determination of permeability (only a function of the medium) whereas the flow log is a method for determination of the hydraulic conductivity (both a function of fluid and medium). However, in connection with the present investigations dealing with "cold" groundwater the permeability and hydraulic conductivity are practically equal and the unit m/sec is used for both.

Granulometric method

The most detailed investigations for determination of the storage aquifer permeability has been carried out by means of granulometry. A method developed by Beyer and Schweiger (1964) (Ref. 7) based on grain size distribution curves has been applied. It is a graphical method based on Hazens formula:

$K = c \times d10^2$ where:

K = permeability
c = proportionality factor
d10 = grain size at 10% passing

Beyer shows the connection between c and $U = {}^{d60}/d10$ and that c = f(U). Based on 1500 grain-size distribution curves and by comparison with pumping test, and permeabilities from laboratory test a series of graphs have been constructed (Figure 3.13), where permeabilities can be read directly if d10 and U are known.

The permeability distribution of the storage aquifer is illustrated in a block diagram (Figure 3.14). In the sediment laboratory of DGU, a number of 90 sieve analyses have been made, and for each analysis permeability has been calculated. Calculations have been made for samples taken with interval of 1 meter from CW1, PW1, PW2, R3, of 2-3 m from PW3, PW4, IW1 and of 3-5 m from IW6, IW10, IW12, IW14 and IW15.

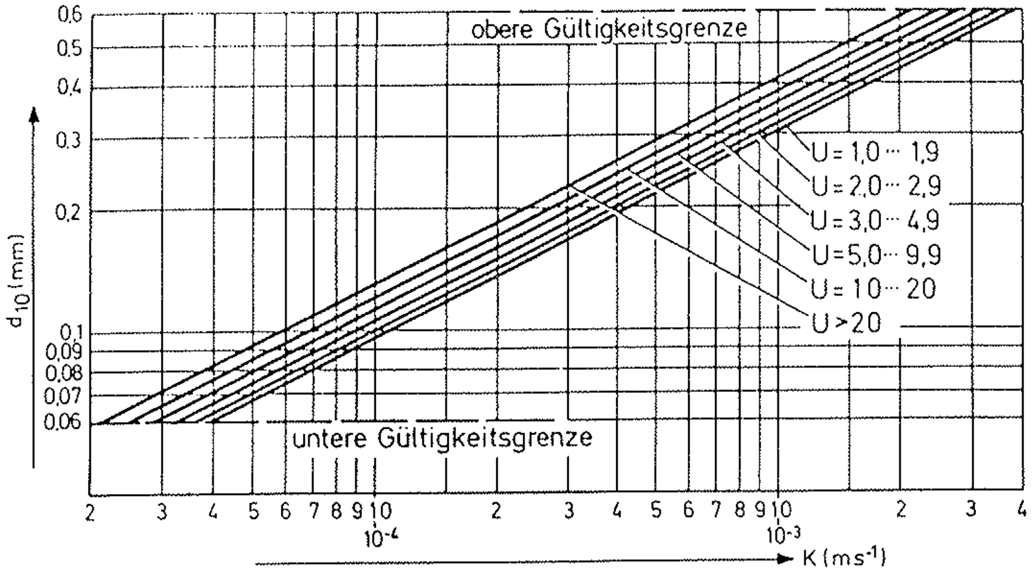


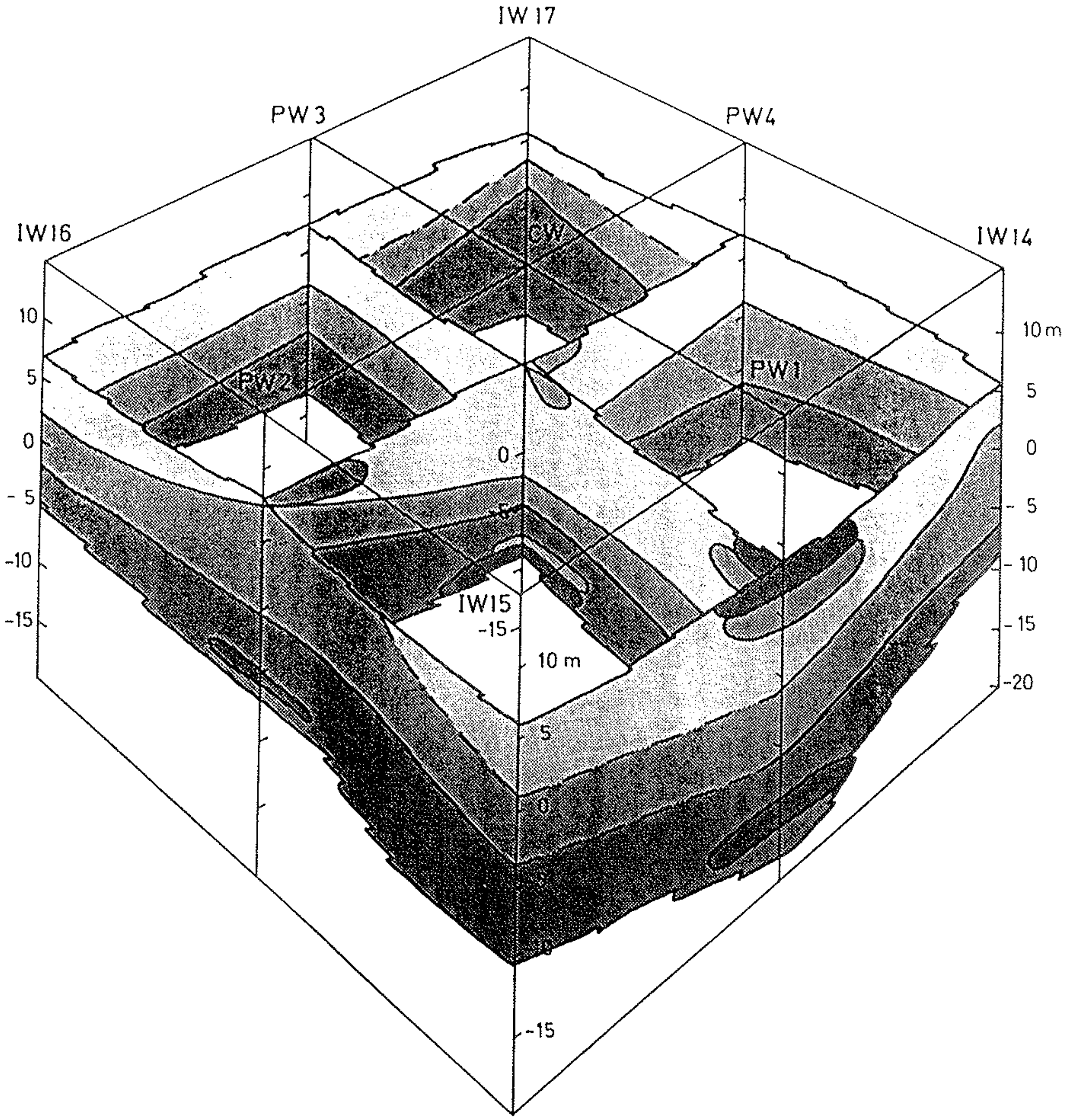
Fig. 3.13 Permeability graphs

Generally, the permeability increases downwards through the aquifer from 0,5 x 10^{-4} m/sec at the top to 1 x 10^{-4} m/sec at the bottom. The heterogeneous zone above the storage aquifer is characterised by changing permeabilities, but is often 0,1-0,5 x 10^{-4} m/sec, which is relatively low permeable. However, the values are uncertain because the grain size distribution of the samples exceeds the validity of the method. Some places in the heterogeneous zone are relatively high-permeable. Examples of this are found in PW1 and PW2 below the upper till, where permeabilities of respectively 1,3 x 10^{-4} m/sec and 0,9 x 10^{-4} m/sec exist. It is obvious that the lowest values are present in the beds of silt and clay. Generally, beds of silt have values around 10^{-5} m/sec and beds of clay values between 10^{-8} and 10^{-12} m/sec, but no calculation have been made in the present investigations.

Below the heterogeneous zone follows 3-8 m of fine sand with permeabilities of 0,5-0,8 m/sec. Downwards the permeability increases further and is around 1 x 10^{-4} m/sec in the lower 6-8 m. A few places it is considerably higher for example at the bottom of CW1 (3,7 x 10^{-4} m/sec). The high permeability here is due to a low coefficient of sorting.

AQUIFER THERMAL STORAGE HØRSHOLM

PERMEABILITY-STORAGE AQUIFER



Permeability K × 10⁴ m/s

	< 0.5		0.5 - 0.8		0.8 - 1.1		> 1.1

Fig. 3.14 Permeability block diagram

The block diagram shows an increase of the permeability down through the storage aquifer from < 0.5 m/sec at the top to > 1.1 m/sec at the bottom.

Flow log

Contrary to the granulometric method the permeability determination from flow log is a direct method. By the flow log method the water flow through the borehole pipe established by pumping is measured by a propeller, which is stepwise moved upwards or downwards through the screened interval.

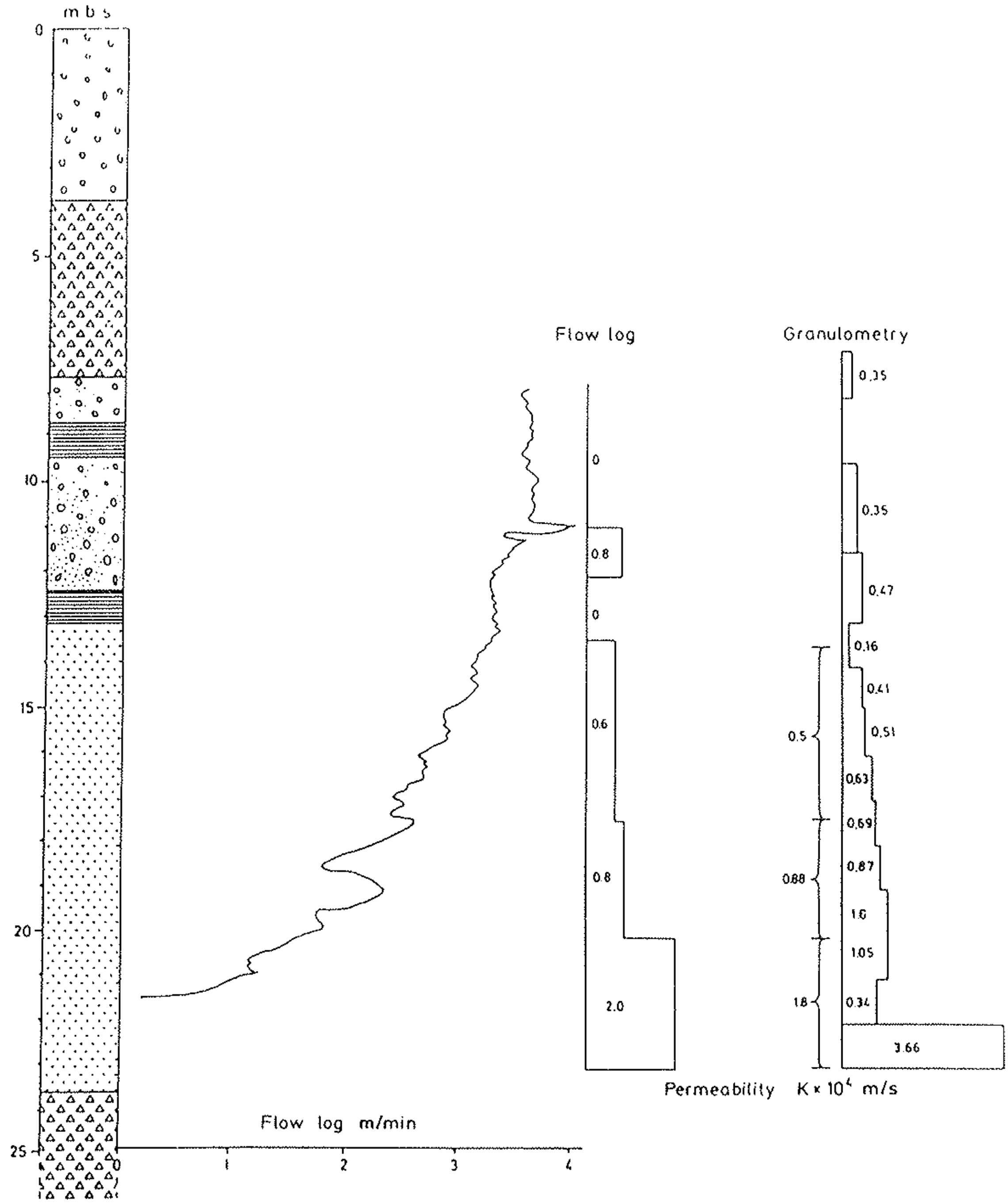
Flow logs have been carried out in the central well CW1 and in the peripheral wells PW1, PW2, PW3 and PW4. However, the peripheral wells are only screened for 5 m, and the method is only reasonable accurate a few meters in the middle of the screened interval. Therefore, it is only the fully screened central well, which is dealt with here.

The flow log and the granulometric permeabilities of CW is shown on Figure 3.15. In the lower part of CW (14-23 m b.s.) the permeabilities from flow log is generally increasing downwards. Compared to the permeabilities from the granulometry the average values differ less than 20%. In the heterogeneous zone (8-13 m b.s.) both the flow log and the granulometric method are uncertain for reasons described in section 6. However, flow log permeabilities indicate that both very low and rather high (0,8 m/sec) permeabilities exists.

Porosity

Determination of the total porosity (n) is based on the uniformity coefficient $U = {}^{d60}/d10$ and that $n = f(U)$. From Figure 3.16.a (Ref. 8) n can be read directly, if U is known. The curve "Mittlere natürliche Lagerung" has been used here. The effective porosity n_o is calculated by means of permeability values and the total porosity. Figure 3.16.b depicts the relationship $S_o = {}^{n_o}/n$ as a function of the permeability (k). With known K, S_o can be determined and with that the effective porosity n_o from $n_o = n \times S_o$.

PERMEABILITY CENTRAL WELL CW_1



The permeability of the storage aquifer in the central well CW 1 has been calculated by flow log and by granalometry (grain size distribution curves). A reasonable agreement exists between the two methods, showing a generally increase downwards from 0.5 x 10^4 m/sec at the top to 2.0 x 10^4 m/sec at the bottom.

Fig. 3.15 Permeability of CW

Determination of the effective porosity (n_o) from the grain size distribution a) Total porosity $n=f(U)$, b) Relative effective porosity $S_o=f(K)$ and with that the effective porosity no from $n_o=nxS_o$.

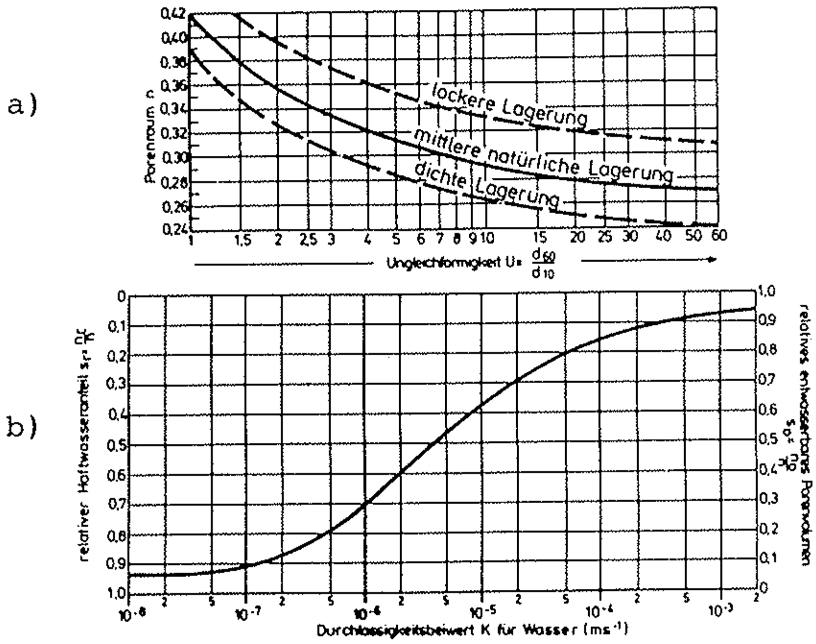


Fig. 3.16 Determination of porosity

The variation of the effective porosity in the storage aquifer is shown on the two cross sections, Figure 3.17. In the finely grained aquifer sand below the beds of silt and clay the n_o values are from 27 to 30%, lowest at the top and increasing towards the bottom of the aquifer. At the bottom of CW1, however, the porosity is up to 33%. In the heterogeneous zone between the clay/silt beds the variations are from 21-30%. It is obvious that the few analyses in the heterogeneous zone do not give a true picture, but the tendencies are probably correct.

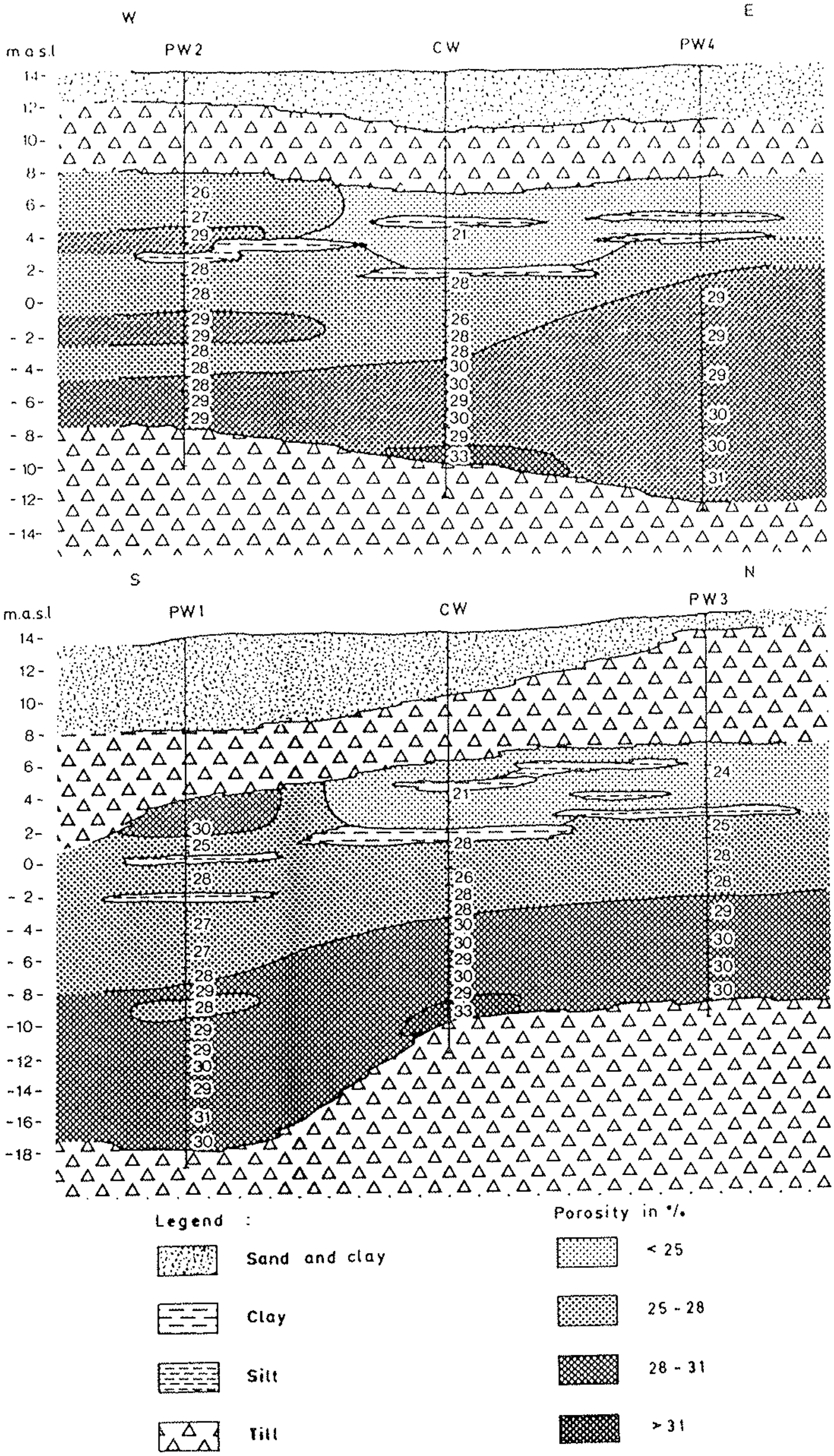


Fig. 3.17 Effective porosity of the storage aquifer
The two cross sections show the effective porosity (n_0) of the storage aquifer. A general increase down through the aquifer from 25-28 % at the top to 30-33 % at the bottom is obvious.

Transmissivity, storativity, leakage

Several pumping tests have been carried out during the different stages of the project. The aim of the pumping tests was twofold - firstly, the hydraulic properties of the storage aquifer should be determined and secondly, the character - (leakage, distribution) of the confining bed should be clarified. The role of the pumping test in connection with the site investigations have been described in section 3.1.4 - here the final interpretation of the pumping test including transmissivity, storativity and leakage through the confining bed will be made.

The shape of the major part of the time-drawdown graphs (double logarithmic paper) is almost similar and can be exemplified by Figure 3.18. Data of the first 50-70 minutes coincides with the Hantush type curve for leaky aquifers with storage in the confining bed. When the cone of depression extends outside the confining bed in the directions of north and west, the drawdown rate is reduced; firstly, due to water table condition and secondly, to leakage through the confining bed. These two effects are impossible to separate on the data curves and make interpretation very difficult. Several of the data plots could be reasonably matched with leakage or delayed yield-type curves and misinterpretation could easily have been the result if the geology and the aquifer conditions have not been so well known. Consequently the hydraulic properties of the aquifer have been calculated by matching type curves (leaky aquifers with storage in confining bed) with data points of the first 50-70 minutes of the pumping tests.

The transmissivity (T) is fairly constant within the investigated area and especially within the storage area. The transmissivity of the storage aquifer in the storage area $T = 1{,}2\text{-}1{,}4 \times 10^{-3}$ m^2/sec is very well verified with similar values of both time drawdown (Figs. 3.19, 3.20, 3.21 and 3.22) and distance-drawdown (Figure 3.23) plot.

PUMPING TEST

VARMELAGRING - HØRSHOLM

Observation Well Data, Pumped Well - DGU file no.194.655

Set up, date 08.01.80 time 12.00 Shut off, date 10.01.80 time CA 4.

Pumping Capacity, Q = 21.5 m3/h

DGU file no.	Distance (m)	T (m2/s)	S	S'	K'/b' (s-1)	Kr/Kz
194.654	92.9	0.0015	3.6E-4	0.01	5.0E-9	

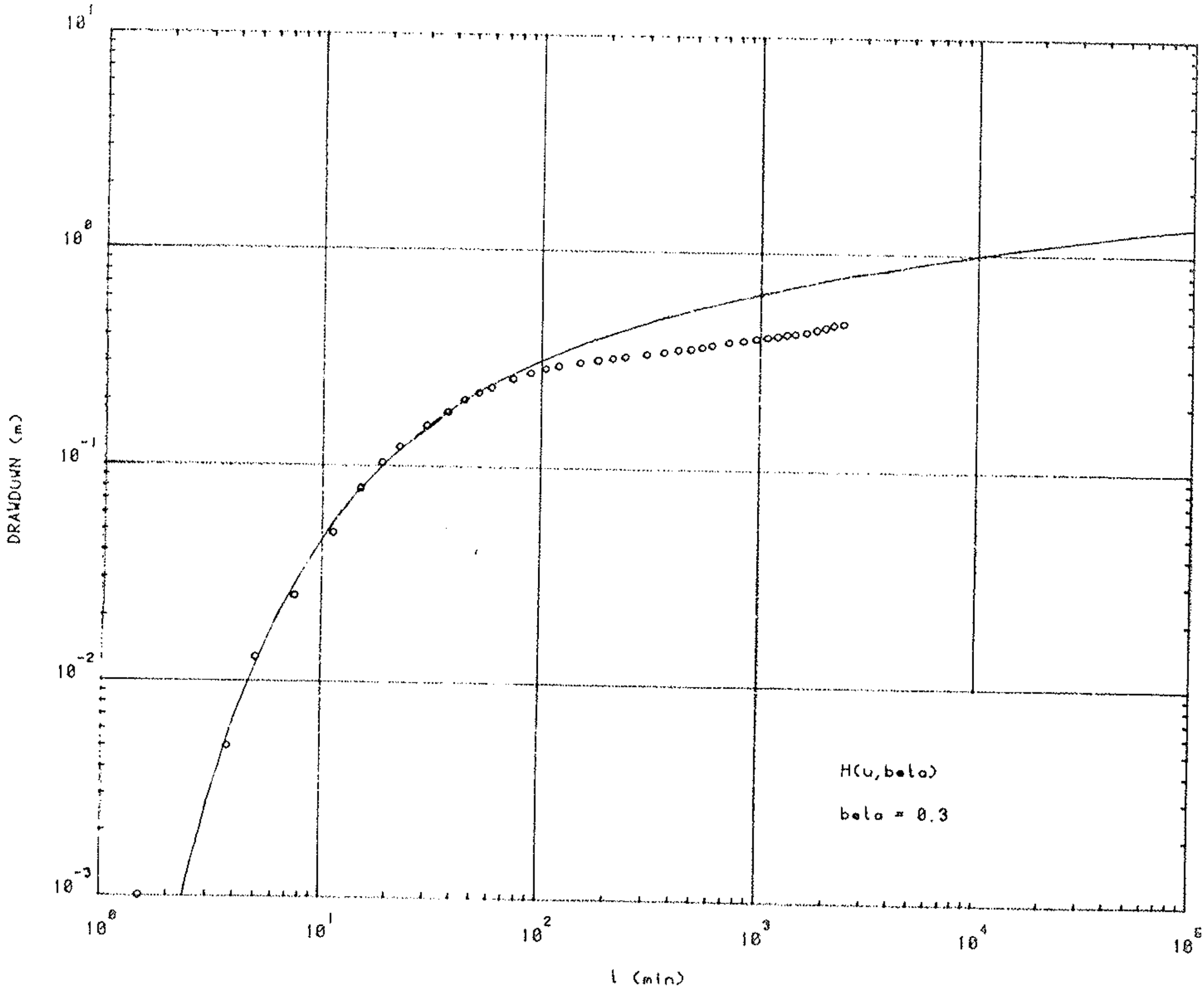


Fig. 3.18 Shape of time-draw-down graphs

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GEOLOGICAL SURVEY OF DENMARK

PUMPING TEST

VARMELAGRING - HØRSHOLM

Pumping Well Data , DGU file no.194.666, CW 1

Set up, date 14.06.82 time 14.17 Shut off, date 18.06.82 time 17.45

Drawdown: T = 0.0013 m2/s

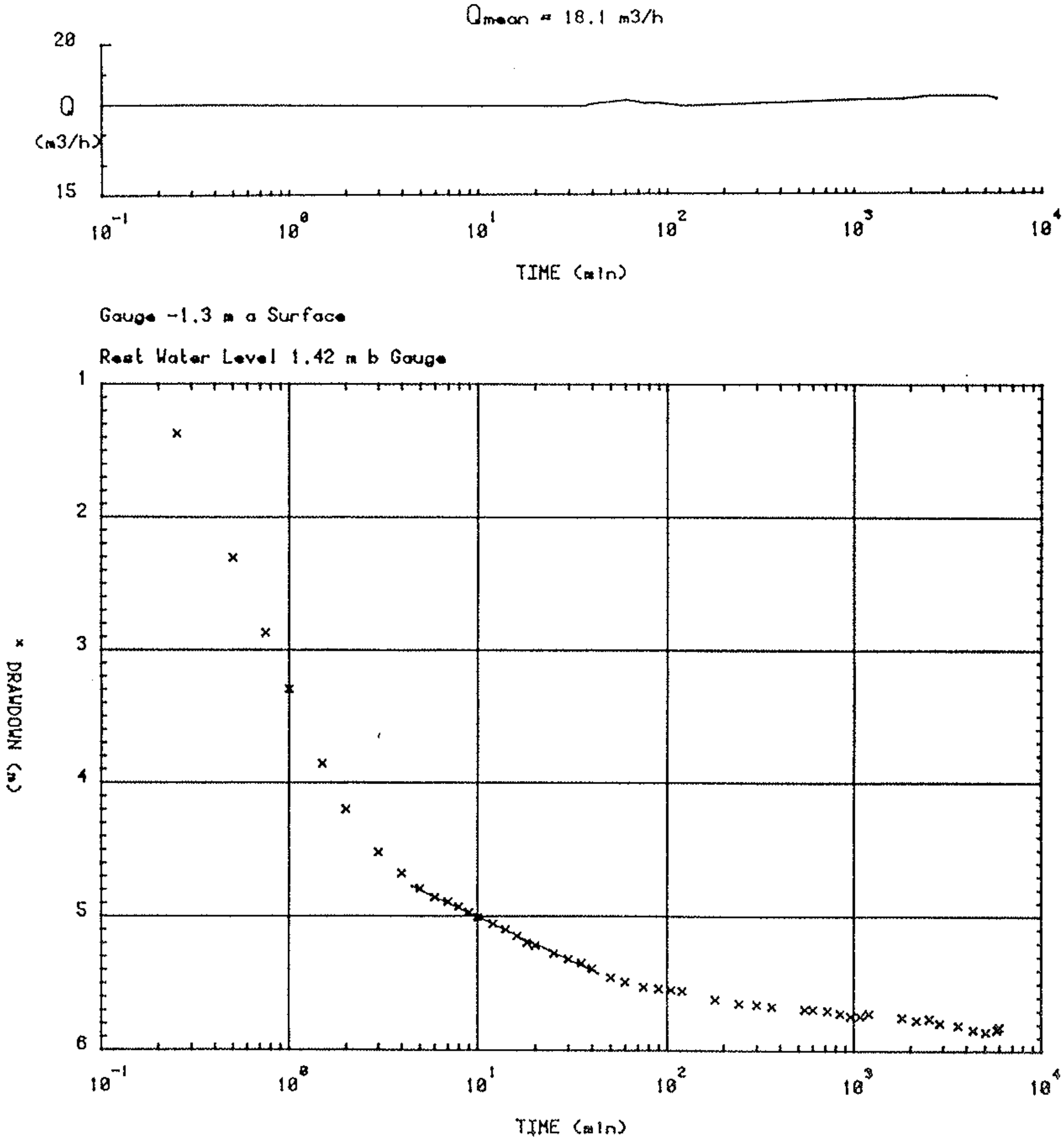

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Fig. 3.19 Time-draw-down plot, CW 1

PUMPING TEST

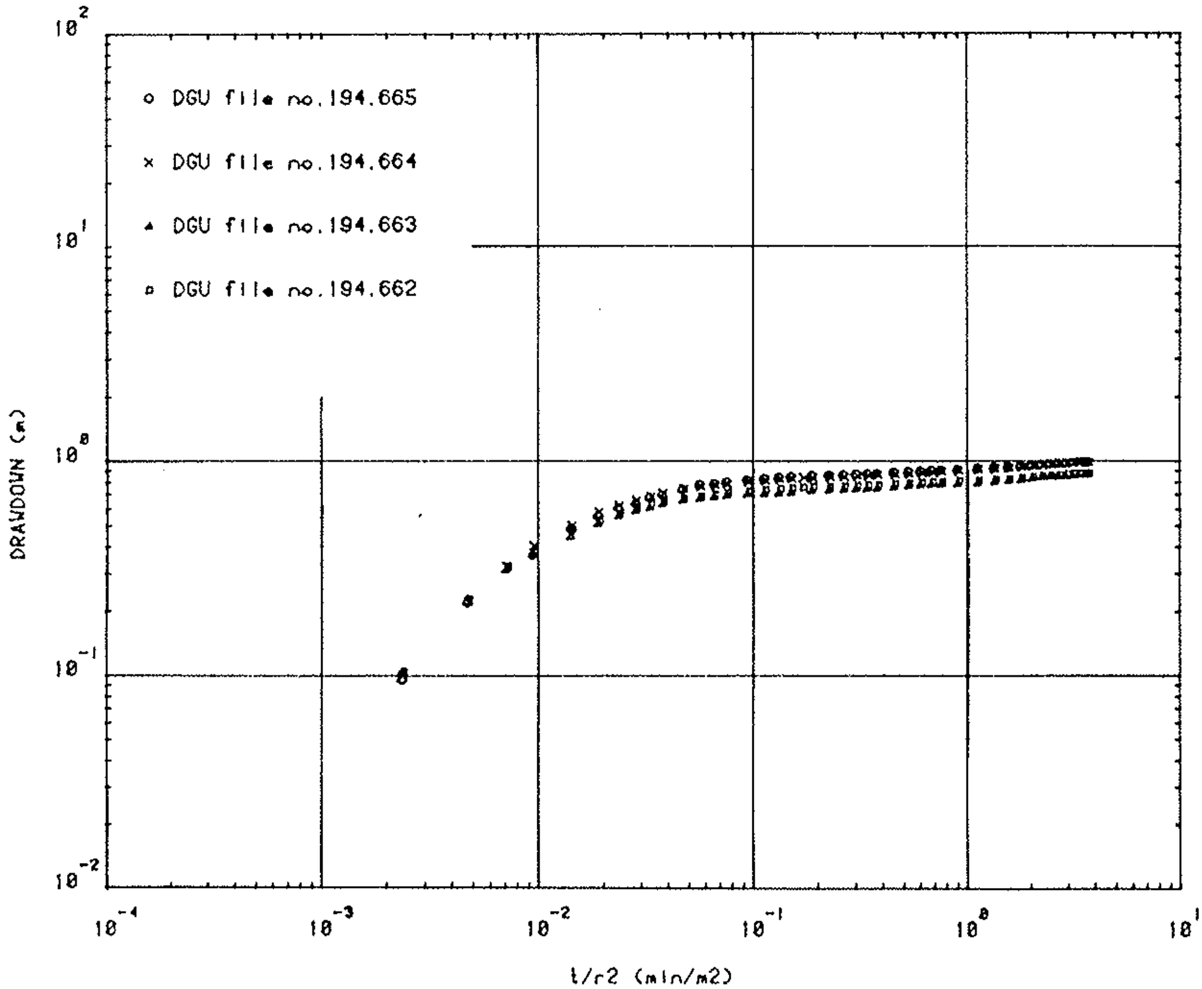
VARMELAGRING - HØRSHOLM

Observation Well Data, Pumped Well - DGU file no.194.666 cw1

Set up, date 14.06.82 time 14.17 Shut off, date 18.06.82 time 17.45

Pumping Capacity, Q = 18.1 m3/h

	DGU file no.	Distance (m)	T (m2/s)	S	S'	K'/b' (s-1)	Kr/Kz
PW 1	194.665	40	0.0011	4.5E-4	0.002	5.0E-9	
PW 2	194.664	39.7	0.0011	4.7E-4		5.0E-9	
PW 3	194.663	39.9	0.0014	4.5E-4	1.0E-3	5.0E-9	
PW 4	194.662	39.6	0.0013	4.5E-4	1.0E-3	5.0E-9	



23.06.86 jk GEOLOGICAL SURVEY OF DENMARK

Fig. 3.20 Time-draw-down plot, PW 1, PW 2, PW 3, PW 4

PUMPING TEST

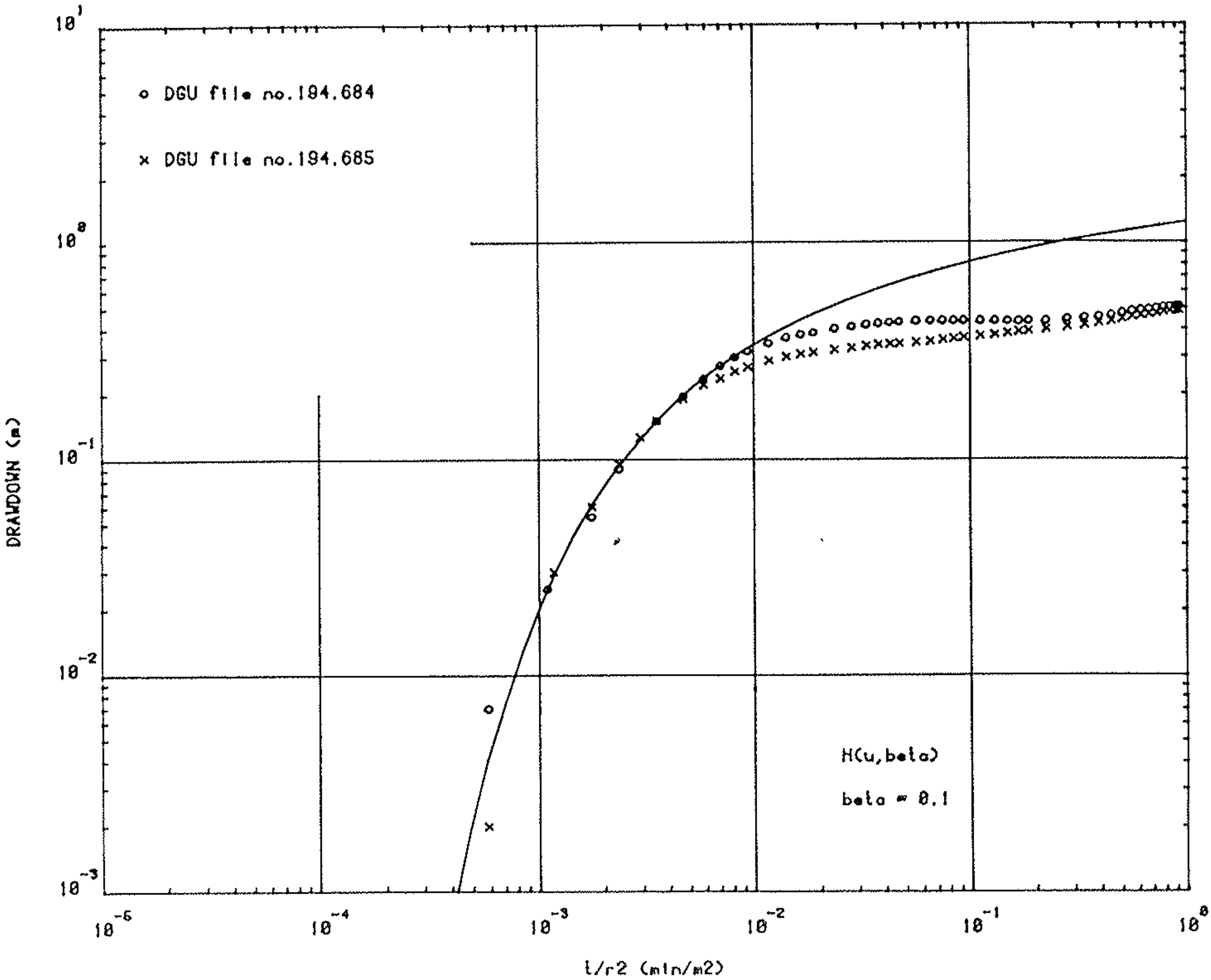
VARMELAGRING - HØRSHOLM

Observation Well Data, Pumped Well - DGU file no.184.666, CW 1

Set up, date 14.06.82 time 14.17 Shut off, date 18.06.82 time 17.45

Pumping Capacity, Q = 18.1 m3/h

DGU file no.	Distance (m)	T (m2/s)	S	S'	K'/b' (s-1)	Kr/Kz
AP 184.684	80	0.0012	4.0E-4	0.002	5.0E-9	
AI 184.685	79.9					



18.06.00 'k

GEOLOGICAL SURVEY OF DENMARK

Fig. 3.21 Time-draw-down plot, AP, AI

PUMPING TEST

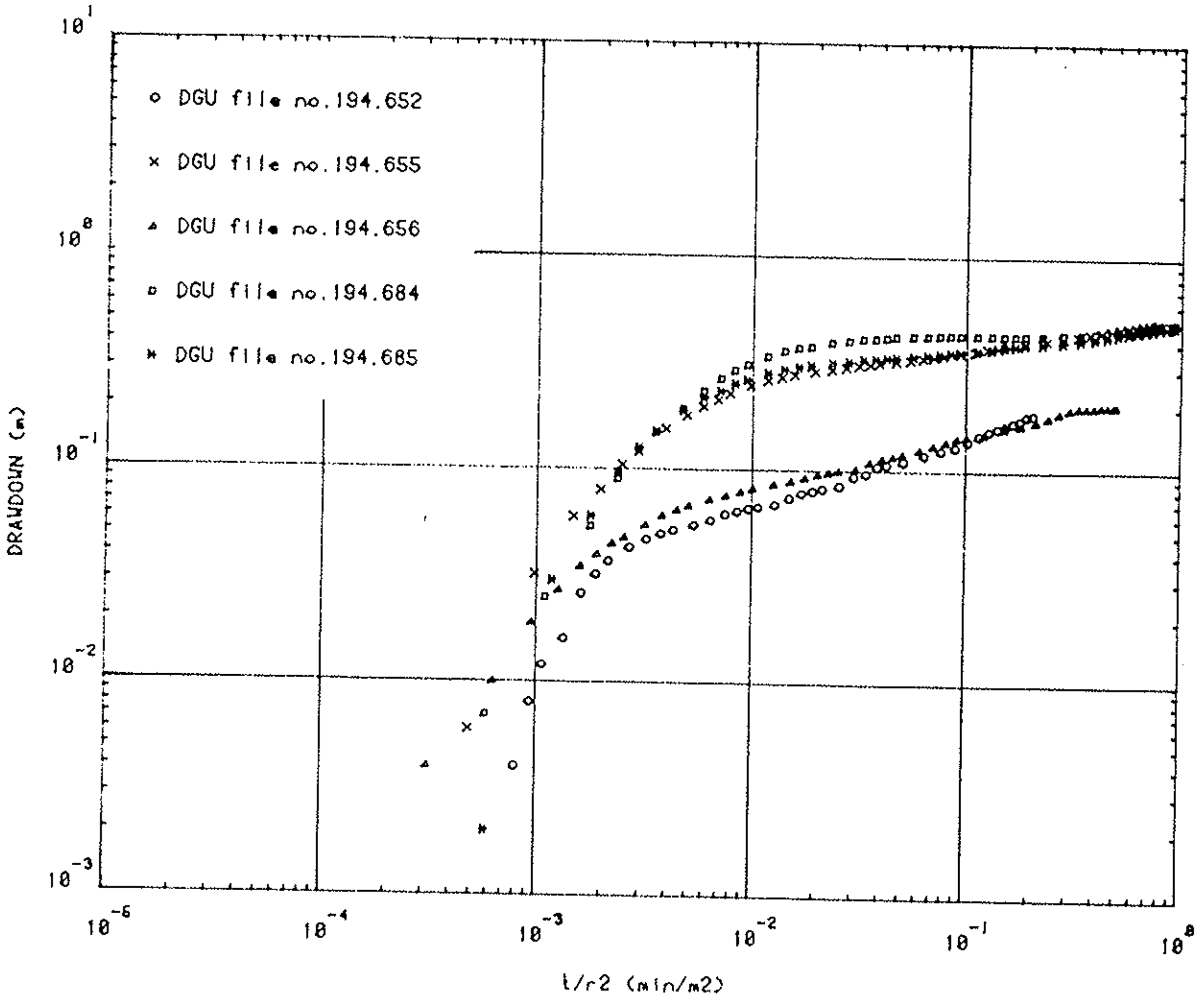
VARMELAGRING - HØRSHOLM

Observation Well Data, Pumped Well - DGU file no.194.666,CW1

Set up, date 14.06.82 time 14.17 Shut off, date 18.06.82 time 17.45

Pumping Capacity, Q = 18.1 m3/h

	DGU file no.	Distance (m)	T (m2/s)	S	S'	K'/b' (s-1)	Kr/Kz
R 1	194.652	167.6	0.0013	5.9E-4	0.007	5.0E-9	
R 4	194.655	87.5	0.0013	3.1E-4	0.01	5.0E-9	
R 5	194.656	109	0.0035	6.1E-4	0.05	5.0E-9	
AP	194.684	80	0.0014	4.8E-4	0.003	5.0E-9	
AI	194.685	79.9	8.0E-4	3.1E-4	0.01	5.0E-9	



23.06.86 jk

GEOLOGICAL SURVEY OF DENMARK

Fig. 3.22 Time-draw-down plot, R 1, R 4, R 5, AP, AI

PUMPING TEST

HØRSHOLM

Observation Well Data, Pumped Well DGU file no.194.666 CW 1.
Set up, date 14.06.82. time 14.17
Shut off, date 18.06.82. time 17.45
Pumping capacity 18.1 m^3/h.
$T_{120} = 1.34 \times 10^{-3}\ m^3/sec.$
$S_{120} = 7.5 \times 10^{-4}$

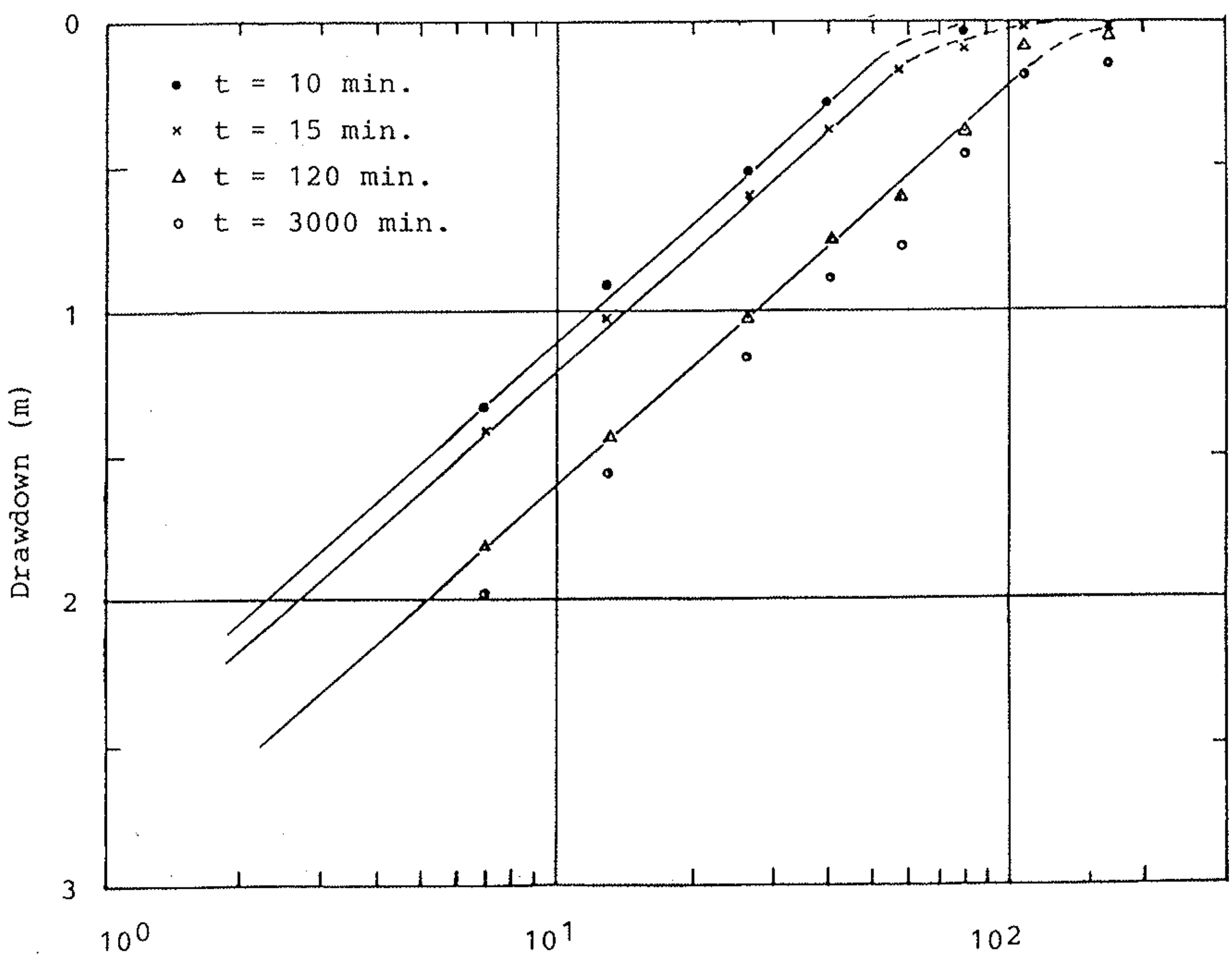


Fig. 3.23 Distance-draw-down plot

The coefficient of storage (S) is about 4×10^{-4}, but is of minor importance in connection with heat storage.

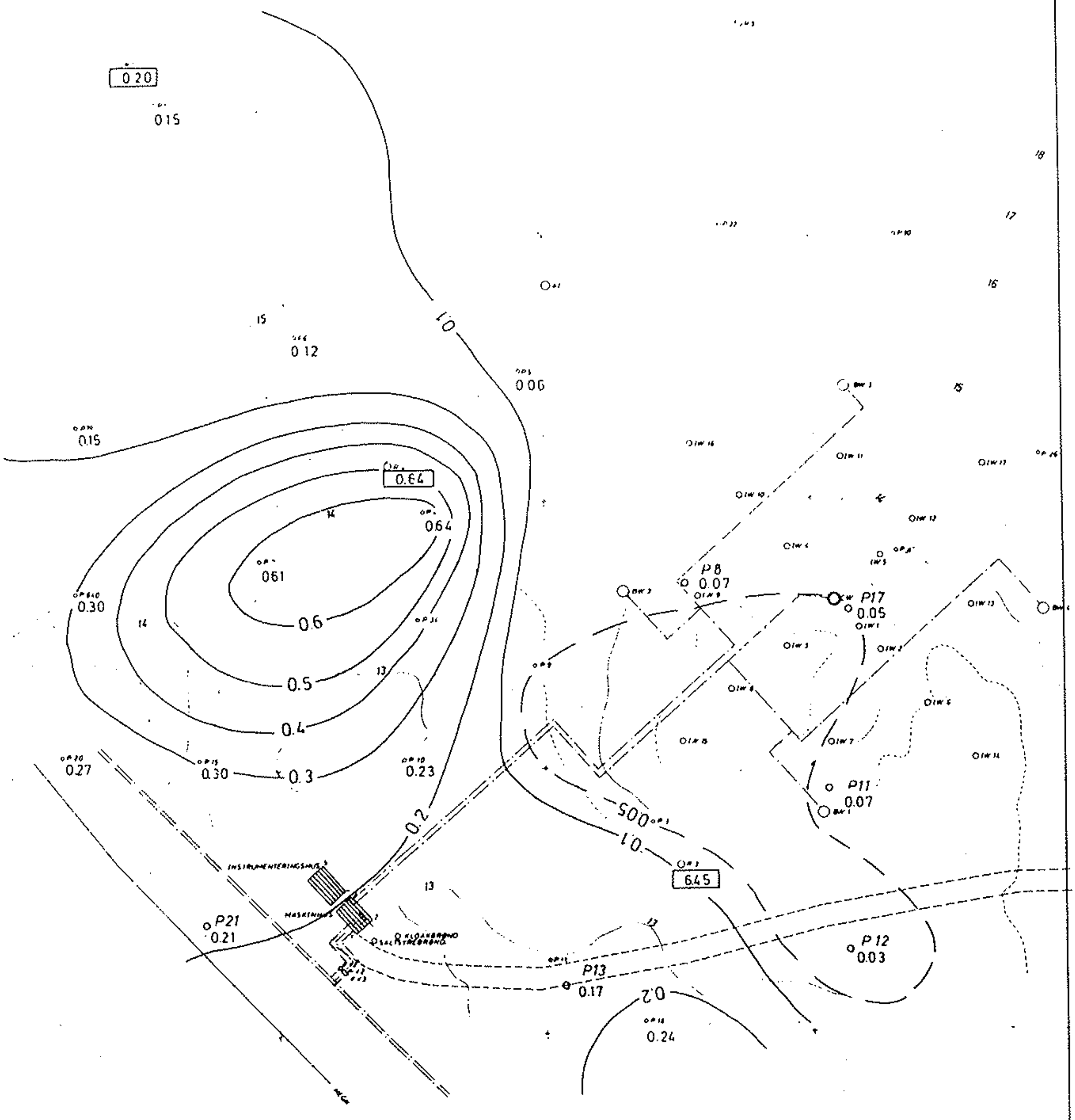
Figure 3.20, where the data plots of the four peripheral wells almost coincide indicates a homogeneous aquifer in agreement with the geological interpretation of the area. Towards north (R5) the pumping test indicate an increase in transmissivity (Figure 3.22), which corresponds to an increase in thickness of the aquifer (Figure 3.12).

The leakage through the confining bed, during the period where the storage effect of the confining bed is the dominating factor, has been determined to be in the order of magnitude of $K'/b' = 1-5 \times 10^{-9}$ sec^{-1}. (Figs. 3.20, 3.21 and 3.22). Similarly the storage coefficient of the confining bed has been calculated to be about $S' = 0,01$.

During pumping of the storage aquifer drawdowns were measured in piezometer tubes in the upper aquifer. Figure 3.24 illustrates drawdowns in the upper aquifer after 3 days of pumping from borehole R3. It is obvious that the largest drawdowns occur around piezometer tube P4 and P7 (> 60 cm), and that they are equal to the drawdowns in the storage aquifer (R4). This indicates a short circuit between the two reservoirs and probably a relatively high leakage through the confining bed in this area. Contrary to this small drawdowns (0,05 m) in the storage area are believed to indicate a relatively impermeable confining bed with low leakage. The similar drawdowns in R1 and P1 supports the hydrogeological consideration of a water table aquifer. These tests and interpretations were important aspects for the final site selection of storage area.

3.3.2 Upper aquifer

The upper aquifer consists of late glacial deposits of sand and gravel. The aquifer lies between 8 and 12,5 m a.s.l. and is downwards limited by the upper till. It is a water table aquifer with water table from 12,5 m in the storage area decreasing to 11,6 m in western parts of the area (Figure 3.1). The water table of the upper aquifer is around 0,5 m higher than the piezometric surface



Drawdowns (m) in upper aquifer after 3 days pumping on R3 (290180). Q = 18.1 m³/h

[0.2] = Drawdowns (m) in storage aquifer.

Fig. 3.24 Draw-downs in upper aquifer after 3 days pumping on R 3 of the storage aquifer (Figure 3.9) but in the western and southwestern part the pressure levels of the two aquifers approach each other and later coincide, constituting a single-water-table aquifer.

A local water divide in the direction northwest-southeast exists in the central storage area. From there water flows to the west - southwest and to the northeast and east. The area around P26 indicating a low, is probably due to a "hole" in the upper confining bed.

The boundary of the upper aquifer to the west and southwest is indicated on the equipotential map, Figure 3.1. This boundary coincides with the boundary of the upper till, Figure 3.2. To the north and east it is not possible to draw a boundary due to lack of data. However, it is believed that the reservoir changes character towards the north. The aquifer becomes more irregular (Figure 3.10) and the permeability decreases because of a higher content of silt and clay.

3.3.3 Groundwater level fluctuations

Groundwater levels have been recorded regularly 1980-1984 in the investigation wells R1-R5 which represent the storage aquifer and in the piezometer tubes P1-P35 which represent the upper aquifer.

The fluctuations in the storage aquifer are generally less than 0,5 m within a year and less than 1 m in the period 1980-1984, whereas the fluctuations in the upper aquifer are much larger, 1-3 m within a year, and sometimes more than 3 m for the period 1980-1984.

In some of the piezometers, (P1, P6, P15, P19, P20, P640) the fluctuations are smaller and generally in the range corresponding to the lower aquifer. This behaviour can be explained by a change from a double aquifer to a single-watertable aquifer system from east to the west and fit with the position of the boundary of the upper aquifer. This change can also be read from Figure 3.25, where P1 and R1, and P4 and R4 fluctuations are almost similar (single-watertable aquifer) whereas P3 and R3 obviously have different fluctuation patterns.

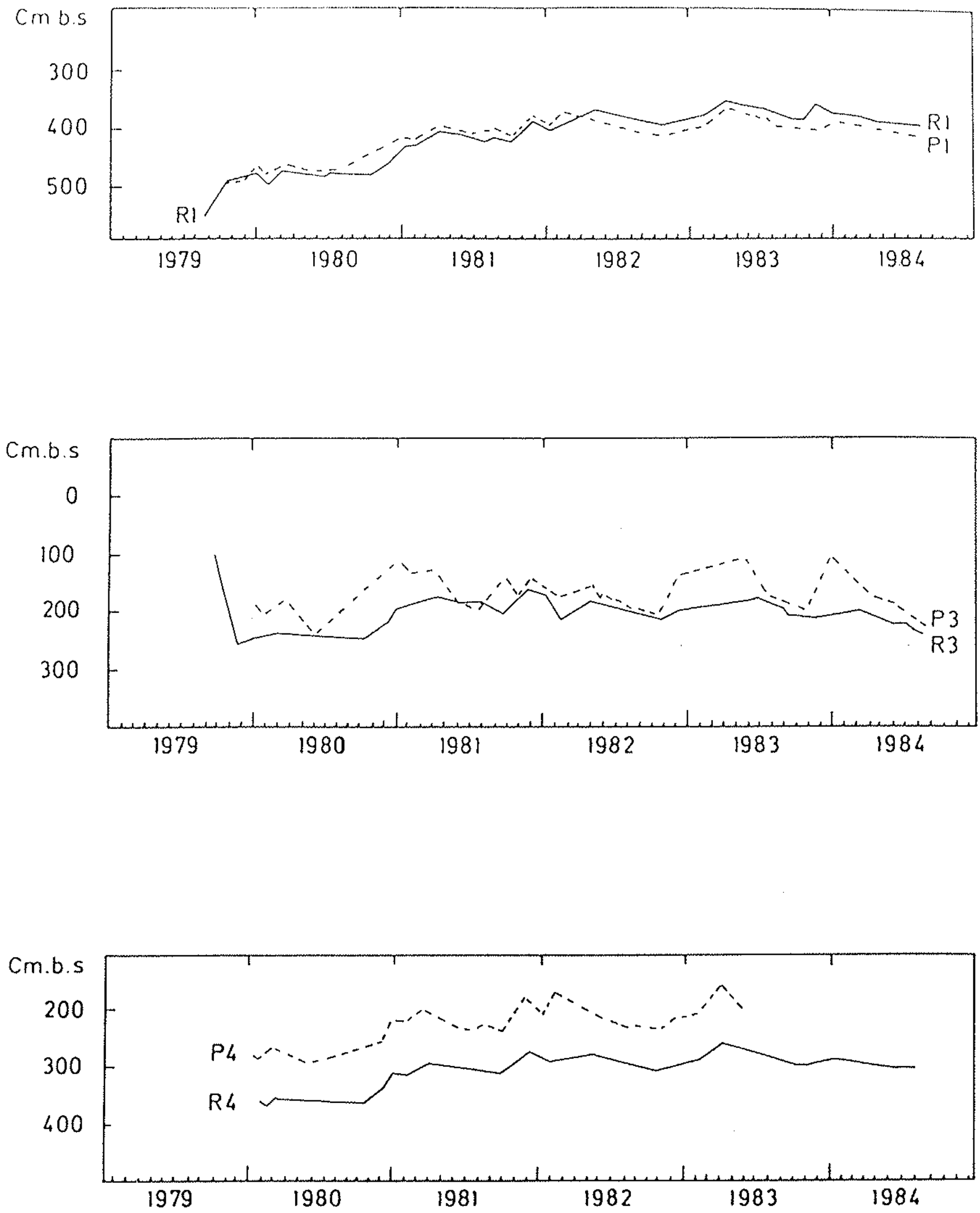


Fig. 3.25 Comparison of groundwater fluctuations in upper and lower (storage) aquifer. P1, P3 and P4 are piezometers in upper aquifer. R1, R3 and R4 are wells in the lower aquifer

4. MATHEMATICAL MODELS

The mathematical models used for thermohydraulic calculations in the design phase of The Danish Aquifer Storage project include several models of different complexity.

Relations between storage capacity and basic geometry are described by simple volumetric considerations whereas detailed studies of buoyancy flow or propagation of the heated zone in the aquifer call for advanced numerical models, that can describe the specific physical processes going on within the store. A summary of the models and examples of their utilisation is given in this section.

4.1 Volumetric calculation

Assuming that the store volume is a cylinder of height H_a (aquifer height) and centre in the injection well, the thermal radius of the store can be calculated from

$$r_e(t)^2 = \frac{(\rho C)_w}{(\rho C)_a} \cdot \frac{V \cdot t}{\pi \cdot H_a} \qquad (1)$$

with

(ρC) : heat capacity of water (suffix w) or aquifer (suffix a)

V : injection rate (average)
t : cummulated injection time

Energy content of the store is given by

$$E = V \cdot t \cdot \Delta T \cdot (\rho C)_w \qquad (2)$$

with

ΔT : temperature difference between injected and produced water.

In Hørsholm the following data are used

$$r_{e,max} = 40 \text{ m}$$

$$H_a = 15 \text{ m}$$

$$(\rho C)_w = 4.18 \cdot 10^6 \text{ J/m}^3 \, ^{\circ}\text{C}$$

$$(\rho C)_a = 2.74 \cdot 10^6 \text{ J/m}^3 \, ^{\circ}\text{C}$$

$$\Delta T = 100^{\circ}\text{C} - 70^{\circ}\text{C} = 30^{\circ}\text{C}$$

From eq. (1) and (2), store capacity, which is the energy content corresponding to the maximum thermal radius, can be calculated. The combination of (1) and (2) can be expressed as

$$E = \pi H_a \cdot r_e^2 \cdot \Delta T \cdot (\rho C)_a \qquad (3)$$

With the data listed above, the capacity equals $6.2 \cdot 10^{12}$ J or 1720 MWh.

4.2 Heat loss model

The efficiency of a store is strongly influenced by heat loss. A numerical model has been used to determine radial heat losses within the aquifer (smearing of the almost-vertical hot water frontier) and vertical heat losses (heat conduction to the confining layers).

Assuming equal injection/production rates and volumes the storage efficiency for the first cycle of a single-well system can be determined from Figure 4.1.

The storage efficiency is defined as the fraction of produced to injected thermal energy, when thermal energy corresponding to temperatures below initial store temperature is disregarded.

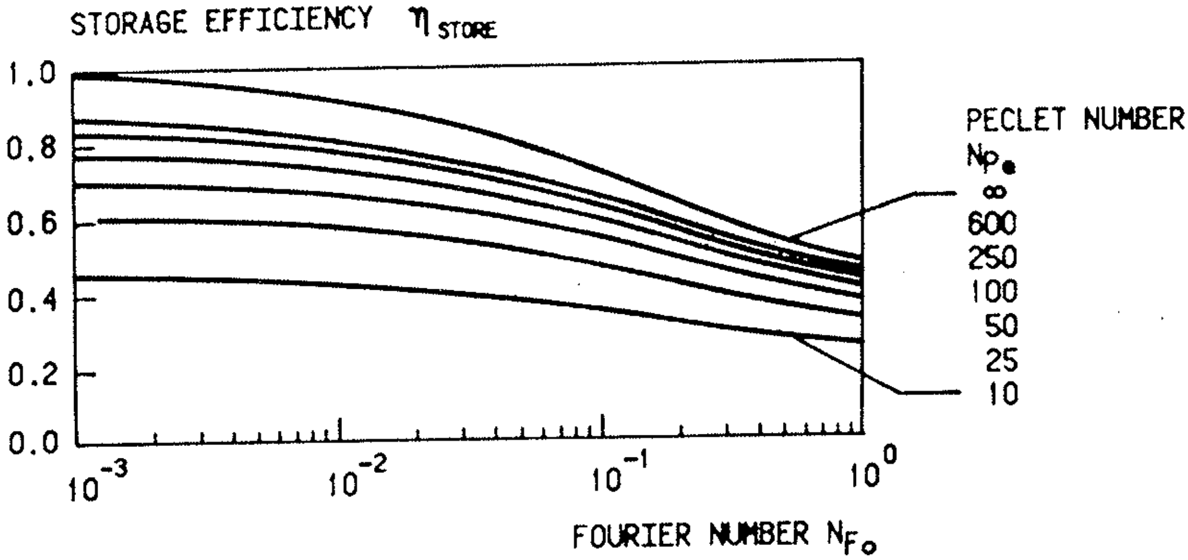


Fig. 4.1 Storage efficiency of the first storage cycle

Two dimensionless parameters are used with the diagram in fig. 4.1. The Fourier number is defined by

$$N_{Fo} = \alpha \cdot \frac{t_c}{H_a^{\,2}}$$

with

$$\alpha = \frac{\lambda}{(\rho C)_a}$$

and the Peclet number

$$N_{Pe} = \frac{(\rho C)_w \cdot \frac{V}{H_a}}{\lambda_e}$$

in which

λ : heat conduction in confining layers

λ_e : heat conduction within aquifer (including dispersive terms) and t_c is the cummulated injection time, which is assumed to be equal to production time.

Using the following data

$\lambda = 3$ W/m °C

$\lambda e = 9$ W/m °C

$t_c = 3$ months $= 7.776 \cdot 10^6$ s

$V = 25.7\ m^3/h = 7.14 \cdot 10^{-3}\ m^3/s$

$(\rho C)_a = 2,74 \cdot 10^6$ J/K m^3 °C

$(\rho C)_w = 4,18 \cdot 10^6$ J/m^3 °C

$H_a = 15$ m

the dimensionless numbers become

$$N_{Fo} = \frac{3}{2.74 \cdot 10^6} \cdot \frac{7.776 \cdot 10^6}{15^2} = 3.8 \cdot 10^{-2}$$

$$N_{pe} = \frac{4.18 \cdot 10^6 \cdot 7.14 \cdot 10^{-3}}{9 \cdot 15} = 220$$

Figure 4.1. gives a storage efficiency of 70% with these data.

Due to the assumptions listed above, the computed value of the storage efficiency can not be used for exact energy calculations, but trends in the interdependence of important parameters can be put to use in the design phase for optimizing storage systems.

4.3 Horizontal flow model for 5-well pattern

For the purpose of checking the assumption stated above, that the store volume could be considered cylindrical, was reasonable, a numerical flow model was developed. This model calculates horizontal flow and propagation of the warm front based on the analytical description of flow in a 5-well pattern as used in Hørsholm.
Vertical flows and heat conductions in the reservoir are disregarded.

Figure 4.2. shows a plot from this model that to a large extent supports the axi-symmetric assumption. This result is achieved under the assumption, that a regional ground-water flow is negligible.

In Hørsholm the regional flow in the area is bypassed across the store by means of an upstream producing well and a downstream injection well. The effect of various regional flow rates and bypass rates were studied with this model.

The effect of the regional flow, which is induced by a 3 o/oo hydraulic gradient, turned out to be quite easy to eliminate.

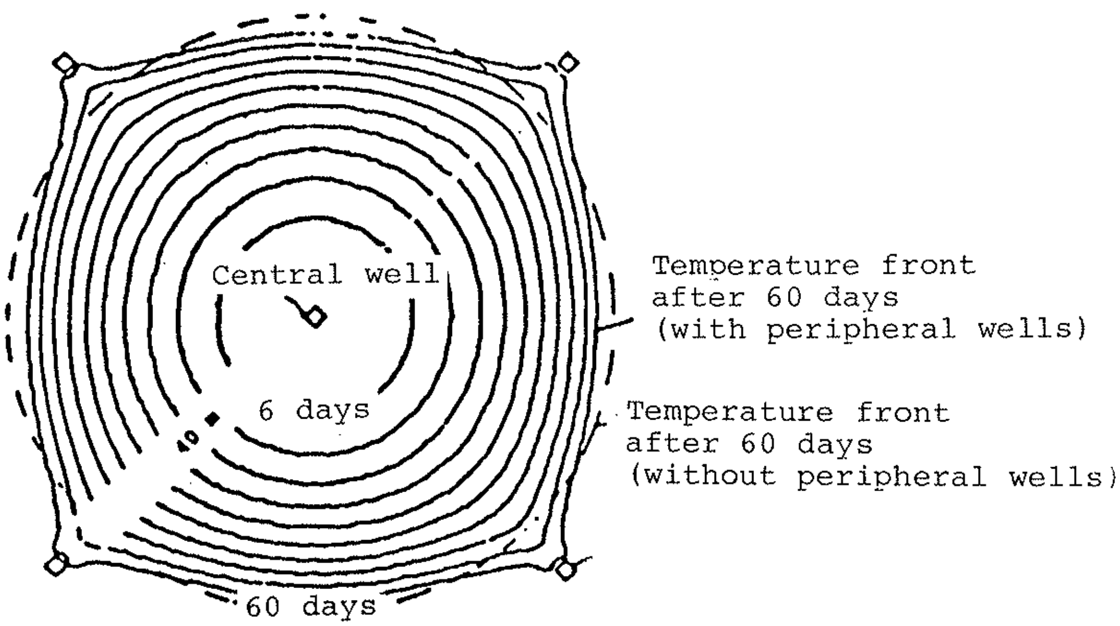


Fig. 4.2 Plot from flow model.

5. THE HEAT SUPPLIER AND CONSUMERS

The store is connected to the district heating system supplied by the incineration plant I/S Nordforbrænding in Hørsholm.

The plant produces heat, primarily by combustion of garbage.

However, during the winter it has to use fuel oil as a supplement. At the time when the plant was established, no garbage was burned during the weekends, and the plant was totally dependent on fuel oil.

During the 4 summer months there was a surplus production of heat, which was rejected through a cooling tower.

In 1978 the plant had a total production of 85098 Gcal; of this 49836 Gcal were generated from fuel oil. The surplus heat, rejected through the cooling tower, amounted to 7246 Gcal.

The rate of cooling in the cooling tower is about 5 Gcal/h in the warmest summer month, on the average. The demand for heat during summer weekends is about 3 Gcal/h. In the coldest winter months, the average fuel-oil generated heat is about 13 Gcal/h.

The forward temperature of the district heating system varies between 90°C and 105°C. The return temperature is about 80°C in the summer, and between 58°C and 65°C in the winter.

The store is connected to a branch of the district heating system supplying heat to a school, a swimming pool and a skating rink.

5.1. Modes of Operation

5.1.1. Storage of heat

During the charging period, the storage system is connected to the district heating network as an ordinary consumer. With the nominal flow of 60 m^3/h, the storage rate is about 2.7 MW (2.3 Gcal/h).

The charging period is the 4 summer months in which surplus heat is produced. The flow path during charge is shown in Figure 5.1.

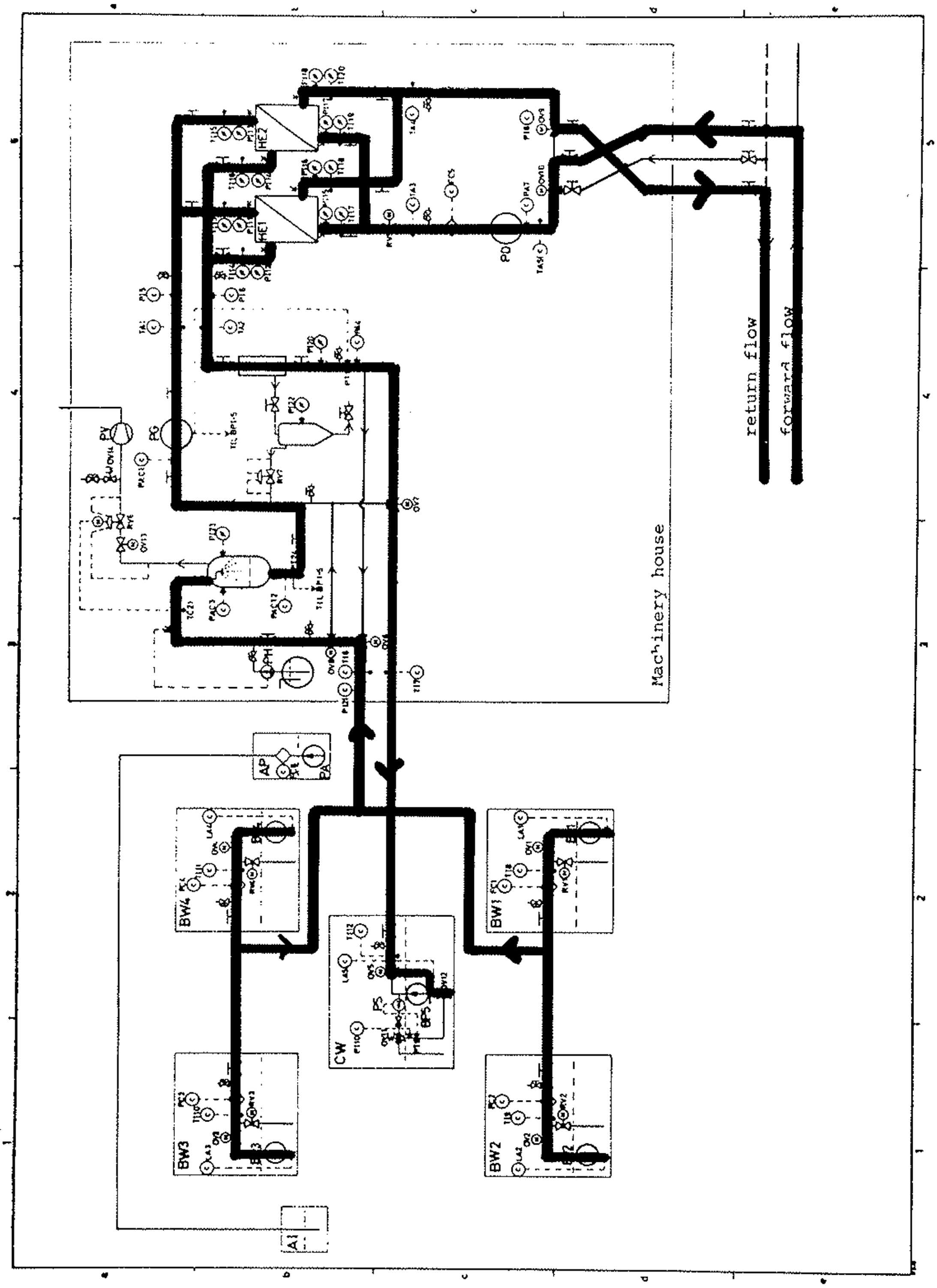


Fig. 5.1 Flow path during storage of heat

5.1.2. Delivery of heat during summer weekends

The delivery flow should be rated so that the resulting amount of heat stored per week would just fill up the storage by the end of storage period. Accordingly, the maximum flow rate is calculated to be about 80 m^3/h. The return temperature of the district heating system is about 80^oC in the summer.

The corresponding heat rate is about 1.7 MW (1.5 Gcal/h).

Most practically, the heat would be delivered to the return pipe of the district heating system. In that way it would be possible to deliver heat as long as the delivery temperature is higher than the return temperature. But during the summer the flow rate in the return pipe of the branch of the district heat system is too small. Therefore, return water from the main line has to be pumped through the return pipe to the storage, and the heat must be delivered to the forward pipe. The flow path is shown in Figure 5.2.

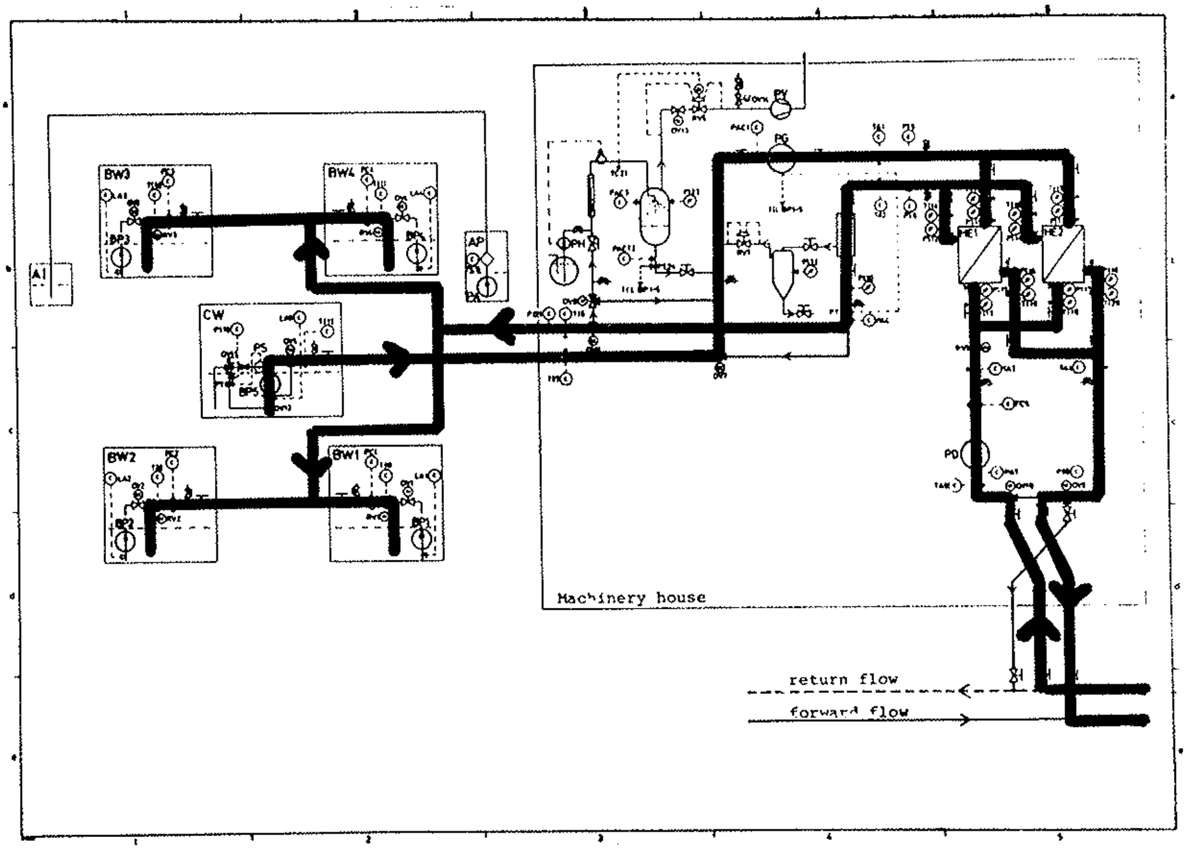


Fig. 5.2 Flow path during delivery of heat

During the period of establishment of the plant the operational schedule of the incinerator plant was changed, so that garbage now was burned in weekends, too. Heat has therefore never been returned during summer weekends.

5.1.3. Delivery of heat in autumn

In autumn, the heat is delivered to the return pipe. The flow path is shown in Figure 5.3. With the nominal flow of 60 m^3/h, and a return temperature of the district heating system at about 65^oC, the delivery rate is about 2.3 MW (2.0 Gcal/h).

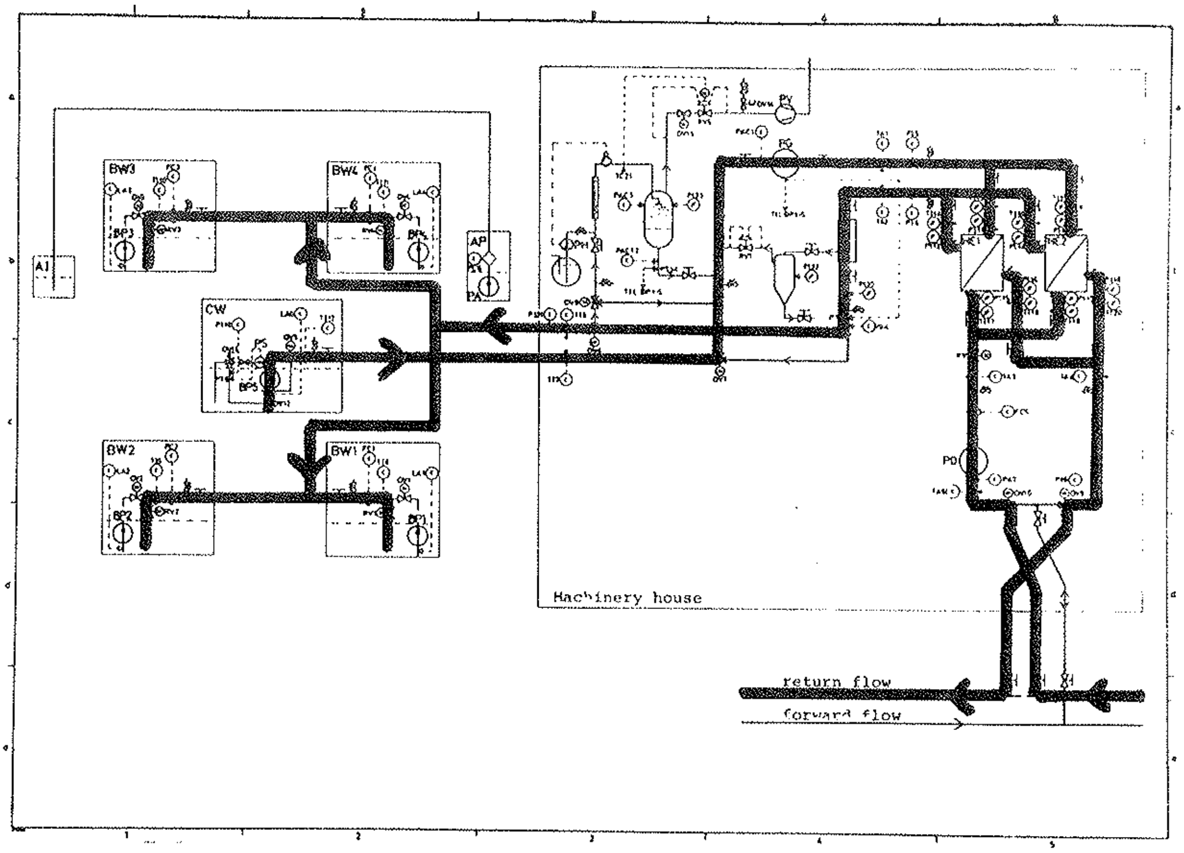


Fig. 5.3 Flow path during heat delivery in autumn

6. OUTLINE OF THE DEMONSTRATION PLANT

Six wells have been established for injection and retraction of water from the store:

2 wells in the middle of the store, the central wells (the reasons for establishing a second central well is described below), and 4 smaller wells (the peripheral wells) distributed on a circle around the central wells.

A map of the area is shown in Figure 6.1. In this map it is seen that the two central wells are connected to the four peripheral wells through two heat exchangers in the machinery house. These two heat exchangers are connected to the incinerating plant, Nordforbrænding.

The machinery house contains the heat exchangers, booster pumps for groundwater and for district heating, and various on/off valves and a acid-treatment system.

The instrumentation house is located along side the machinery house. Here a local minicomputer, Macsym, is placed. This computer collects data such as water flows, temperatures and pressures in the store every 3 minutes. Furthermore, a terminal, which is connected to the host computer, RC 8000, at Risø through a telephone line is located in the instrumentation house. The data are processed at Risø.

The machinery house and the instrumentation house are placed 150 meters from the central wells.

On the map in Figure 6.1 17 instrumentation wells, IW are also shown. In each instrumentation well temperature sensors are placed at different levels in the store. These temperatures are registered by the computer in the machinery house and transmitted to RC 8000 at Risø. In each of the four instrumentation wells, IW 1, IW 2, IW 6 and IW 14, that are located on one radius, pressure sensors have been placed. The pressure sensors are used to register rise/decline of the water level in the store during production or injection from the central well. These changes in water level are also registered at the computer in the machinery house and transmitted to RC 8000 at Risø.

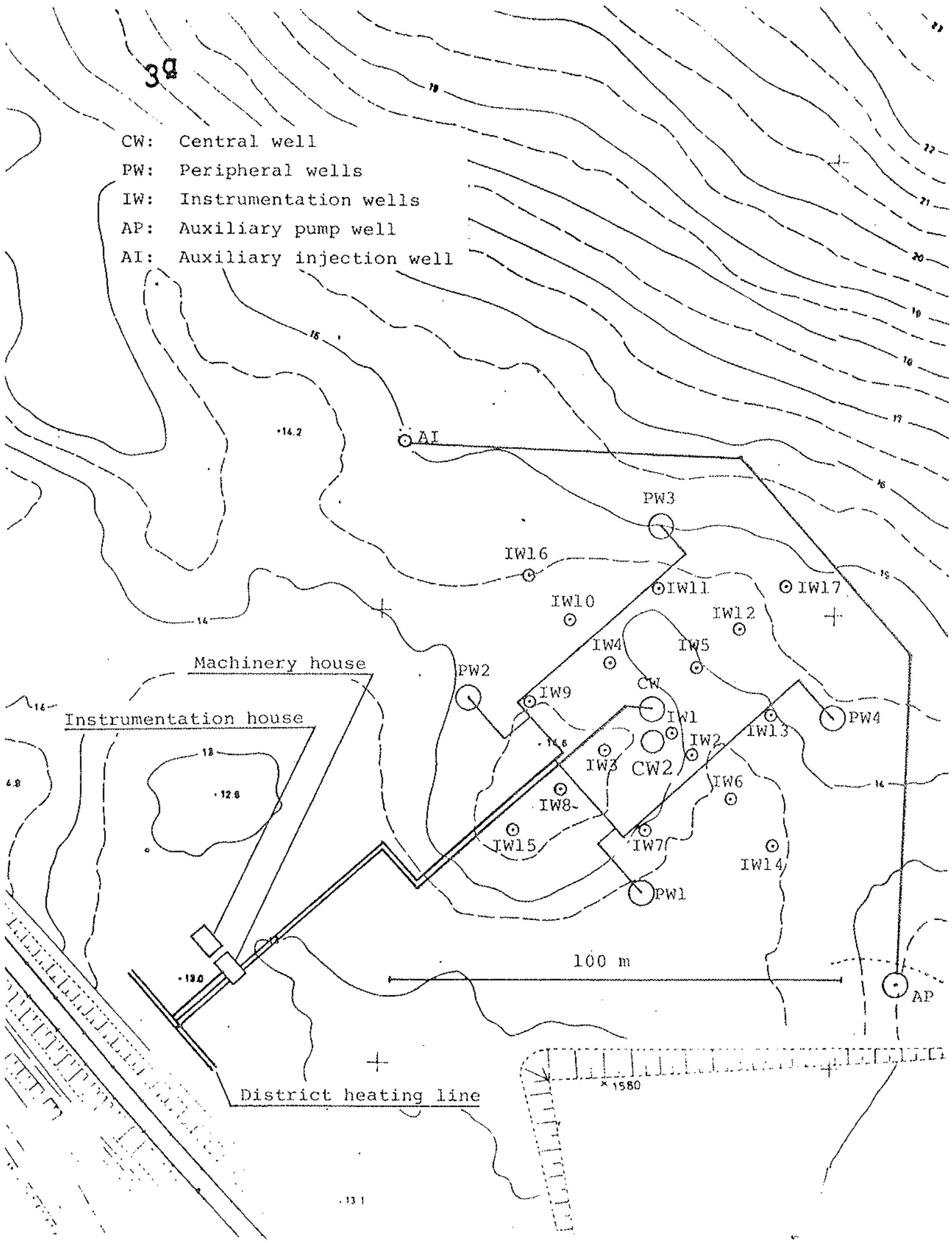


Fig. 6.1 Map of the storage area

Furthermore, on the map two auxiliary wells are shown. The purpose of these two wells is to compensate for the regional ground water flow, which is done by pumping from the upstream well to the downstream well.

The peripheral wells are placed at the periphery of a circle with a diameter at 80 meters. The central well, CW 1, is placed at the centre of this circle. The other central well, CW 2, is placed 6 meters south west of CW1. The store was originally established (1982) with only one central well, but several leaks arose near the central well in the years of 1983 and 1984 and it was decided to establish a new central well to be used for injection. This new central well was established in 1985.

The geology in the storage area limits the extent of the store and hence its capacity. The store is confined upwards by a layer of clay at a depth of 10 meters and downwards by a layer of clay at a depth of 25 meters. The distance between the two layers of clay (the reservoir thickness) is not constant over the entire storage area, because of a 1-2% sloping of the upper layer. The size of the store is limited to a circle with a diameter of about 80 metres by the extent of the upper layer of clay. The volume of the store is thereby 75 000 m^3.

The heat is stored both in the water in the pores of the store and in the solid material consisting of sand.

The heat capacity depends of the porosity. It is slightly lower than the heat capacity of water, because of the lower heat capacity of sand (about 2,1 $MJ/m^3\ ^oC$). At a porosity of 30%, heat capacity is estimated to be 2,7 $MJ/m^3\ ^oC$.

With a scheduled logarithmic mean temperature difference of 3^oC across the heat exchangers, the storage temperature will be about 100^oC. With an assumed loss of storage temperature of 3^oC, the amount of energy to be recovered in autumn is about 1900 MWh (1640 Gcal/h).

6.1. Piping diagram

The schematic piping diagram for the project is shown in Figure 6.2. All the components in the various wells and in the machinery house are mentioned in the diagram. In the diagram the two central wells, the four peripheral wells, the two auxiliary wells and the machinery house are indicated by dotted lines.

The following designations are used for the various wells and components.

BW	peripheral well
CW	central well
AP	auxiliary well for production
AL	auxiliary well for injection
HV	hand operated valve
OV	on/off valve
OV 12	sleeve valve
RV	regulating valve
BP	borehole pump
PG	booster pump groundwater
PD	booster pump district heating system
PA	auxiliary pump
PS	activating pump for sleeve valve
PH	dosage pump for HCL
PV	vacuum pump
HE	heat exchanger
FC	flowmeter
V	ventilator

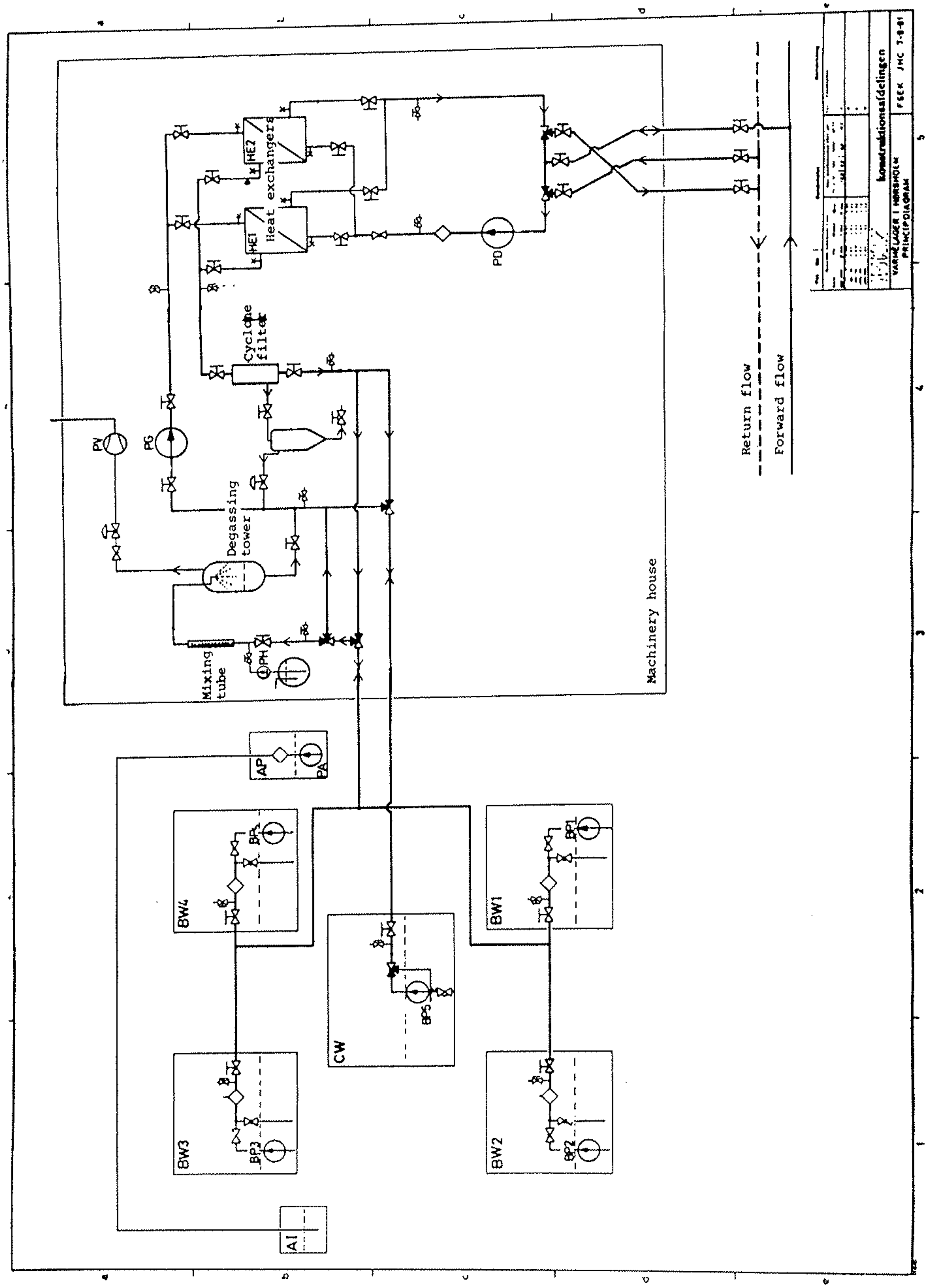


Fig. 6.2 Piping diagram

PI pressure indicator

LA pressure sensor for alarm

TI temperature indicator

TC temperature sensor for control

The schematic diagram shows the directions of the groundwater flow and of the flow of the district heating system.

The groundwater and the water from the district heating system enter the machinery house. These two flows exchange heat in the heat exchangers. In the schematic piping diagram in Figure 6.2 the groundwater flow enters the heat exchangers at the top, while the flow of the district heating system enters the heat exchangers at the bottom.

6.1.1 Groundwater system

Delivery of heat

From CW1, water is pumped by the borehole pump BP5 to the machinery house through OV7. During delivery of heat the water treatment system is bypassed. Therefore HV36 is open, and the booster pump PG pumps the water to the heat exchangers. The heat exchangers are in parallel so that it is possible to uncouple one of them for cleaning when necessary. The water leaving the heat exchangers flows through the filter and OV6 before leaving the machinery house. Now the water enters the peripheral wells. The amount of water entering each well is controlled by regulating valves in the wells. During injection in the peripheral wells the on/off valves placed in the wells are closed to avoid injection of water in the borehole pumps.

Storage of heat

From the peripheral wells the borehole pumps deliver the water to the machinery house through OV6. In the peripheral wells the on/off valves are open and the regulating valves are closed.

The water flows through OV8 and the water treatment system, whereafter the water is pumped by the booster pump PG through the heat exchangers, filter and through OV7 before leaving the machinery house. The heated water flows through OV5 and is injected in CW2.

6.1.2 District heating system

Delivery of heat

During delivery of heat the water from the return pipe in the district heating system is pumped through OV10 to the machinery house. From here, the water is pumped by the booster pump PD through the heat exchangers before leaving the machinery house through OV9 to the return pipe of the district heating system.

Storage of heat

During storage of heat the water from the forward pipe in the district heating system is entering the machinery house through OV10. The water is pumped by the booster pump PD through the heat exchangers. Here the water is cooled and flows through OV9 before leaving the machinery house to the return pipe of the district heating system.

6.2 The piping

The pump stations have been connected to the machinery house by buried, insulated pipes. The pipe material is standard low-alloy steel, as no corrosion problems were expected during the projected life of the research project. The ground water is assumed to be free of oxygen and the concentration of hydrochloric acid added is below drinking water limits. The pipes are insulated by a jacket of polyurethane, coated by water proof PVC on the outside. Such pipes are available commercially as prefabricated modules.

The pipe dimensions have been selected from erosion considerations. The velocity of the water should not exceed 1.5 m/s.

As shown in the diagram, Figure 6.3, the piping has been designed with several 90^{o} bendings, in order to be able to absorb thermal stresses, without the relatively expensive compensators.

The piping in the machinery house is made of steel ST 34. The pipes are isolated with 40 mm mineral wool.

During operation of the plant corrosion in several pipes in the machinery house has appeared. By inspection of the pipes it is seen that the corrosion is very easily apparent at the surface of the pipes. The original thickness of the pipes was about 3,4 mm. In several of the pipes in the machinery house the thickness has presently been measured to about 1,3 mm.

There are two reasons for the corrosion:

1. The presence of oxygen in the water.

2. An overdose of hydrochloric acid.

Several leaks in the system during operation has permitted oxygen to enter into the water on the groundwater-side. The presence of oxygen in the water accelerates the corrosion in the pipes. It is therefore necessary to check frequently for presence of oxygen in the water.

During test of the water treatment plant the dosage of HCl has varied considerably. An accidental pH below 5 may have caused the visible corrosion in the pipes. Today pH is never allowed to sink below 6.7. Under these conditions the presence of the HCl should not affect the corrosion in the pipes.

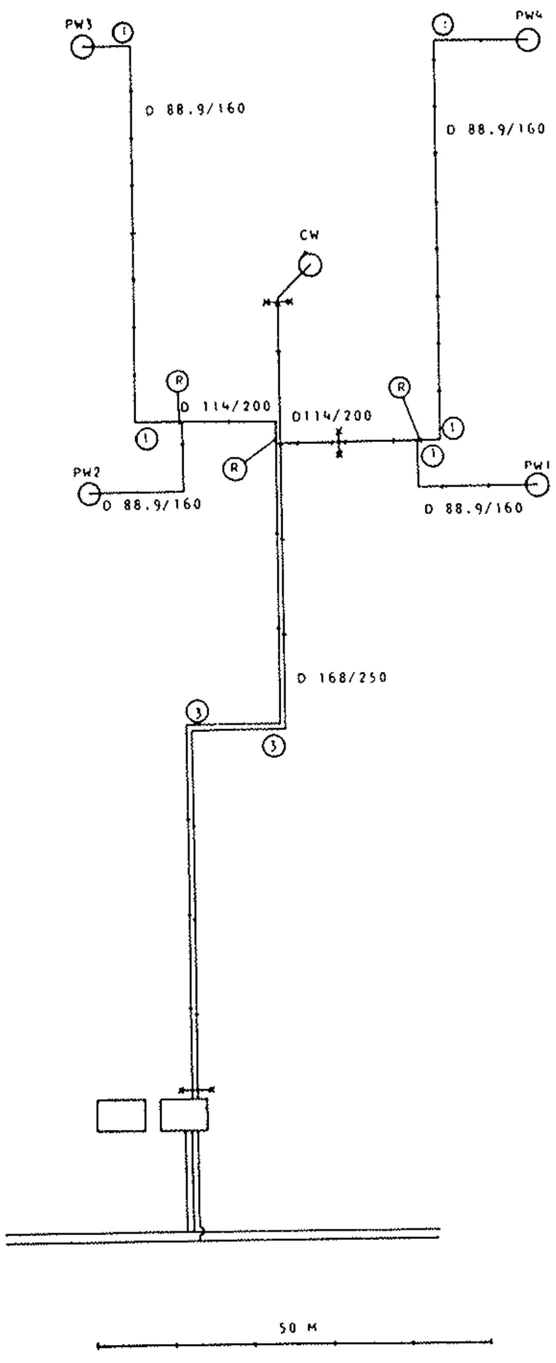


Fig. 6.3 Piping of lay-out.

7. DESCRIPTION OF TECHNICAL ASPECTS OF THE PLANT

7.1 The wells

7.1.1 The central wells

During the initial operation of the store a leak appeared through the upper confining bed 20 m from the original central well CW1. The observed leakage passage appeared to function as a one way valve, opening when the injection pressure exceeded a certain level, but closing during production.

Unsuccessful attempts were made to repair the covering layer. Attempts to inject cement through parts of the screen in the central well also failed and a new central well CW2 was established some distance from the first well, thus reducing the pressure at the leak below a critical level.

CW2 is now functioning as injection well, while CW1 is only used as production well, thus avoiding leakage.

The central well, CW1

The depth of the first central well, CW1, is 25 m. The diameter is 14". The well (shown in Figure 7.1) is equipped with a well screen of 10" throughout the aquifer height, surrounded by a gravel pack, 2" thick.

The following method of drilling which may be called a meticulous conventional method, has been used for the first central well and for the peripheral wells in order to prevent leaks through the upper layer of clay:

1. The conductor pipe has been set 0,5 - 1 m below the top of the layer of clay.

2. The drilling pipe has been drilled in the entire depth. During drilling there has been overpressure in the pipes to

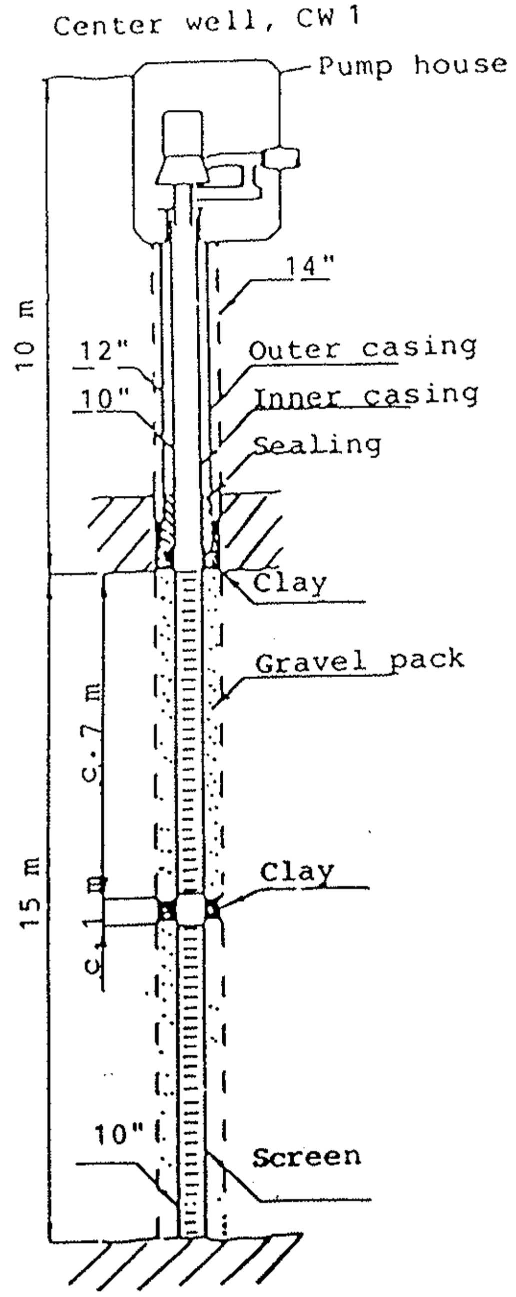


Fig. 7.1 Design of CW 1

avoid cavities below the layer of clay. After setting the drilling pipe, the annulus between conductor pipe and the drilling pipe has been filled up with sludge of concrete to the edge of the conductor pipe.

3. The screen, casing and an insulation pipe of PVC has been set. A gravel packing has been made during withdrawal of drilling pipe to the lower edge of the layer of clay.

4. Expanding concrete has been injected between insulation pipe and drilling pipe up to the ground.

5. The drilling pipe has been drawn up.

6. The conductor pipe has been drawn up during the filling with concrete between the drilling pipe and the conductor pipe.

The screen material is stainless steel, which makes it possible to remove deposits of lime scale by chemical treatment. A casing of stainless steel continues from top of the screen (10 m.b.s.) and up to the pump house floor at the surface. The perforation of the upper layer of clay around the well casing is filled up with bentonite in order to ensure that it is impenetrable to water.

With the intention of making an insulation around the well casing, an outer casing, made from PVC, is placed concentrically to the steel casing. The air-filled, insulating space between the two casings, is sealed with concrete.

The aquifer around CW1 has a higher permeability at the bottom than at the top. For this reason injection in CW1 is carried out in the entire screened interval, while pumping from CW1 is carried out only from the upper part of the screened interval.

A remote-control valve has been placed half-way down the screen for closing off the lower half of the well during heat recovery. The valve selected is a sleeve valve, which can be operated by pressurised water. In the present case the groundwater itself, supplied from the borehole pump is used.

In an attempt to repair the leak through the upper covering layer, the upper half of the screen was cemented. Therefore the remote-control valve is not in use.

The new central well, CW2

The new central well is located at a distance of 6 m from the first central well.

By establishment of the new central well, another method of drilling has been used than by establishment of the rest of the wells.

The used method of drilling is called reversed circulation:

1. A reservoir has been established.

2. The conductor pipe has been set to the middle of the layer of clay.

3. Reversed circulation: The drilling is affected by overpressure of water from the reservoir to which is added geletine. Simultaneously the reservoir is filled with drilled material in the form of mud, thus consolidating the formation.

4. Screen and casing has been set. The outer casing has been welded to the screen casing.

5. Gravel packing has been made to 1 m above screen.

6. 1 m expanding bentonite has been injected.

7. Between lower and upper layer of clay, concrete and gravel packing has been set alternately 3 times. In the 3 gravel-packs monitoring pipes have been set to follow the water level during injection.

8. Concrete and bentonite have alternatingly been packed up to 2 m below ground.

9. The conductor pipe has been drawn up during the filling with concrete and bentonite.

To prevent high pressures from developing during injection, CW2 has been equipped with a large screened area. This is to exploit the fact, that the flow friction decreases with increasing screened area.

The design of CW2 is shown in Figure 7.2. CW2 is 24 m deep with a diameter of 28". The screen of stainless steel is 20" and the gravel pack around has a thickness of 4". The screen is placed from 15 to 24 m b.s. and connected to the pump house floor with a

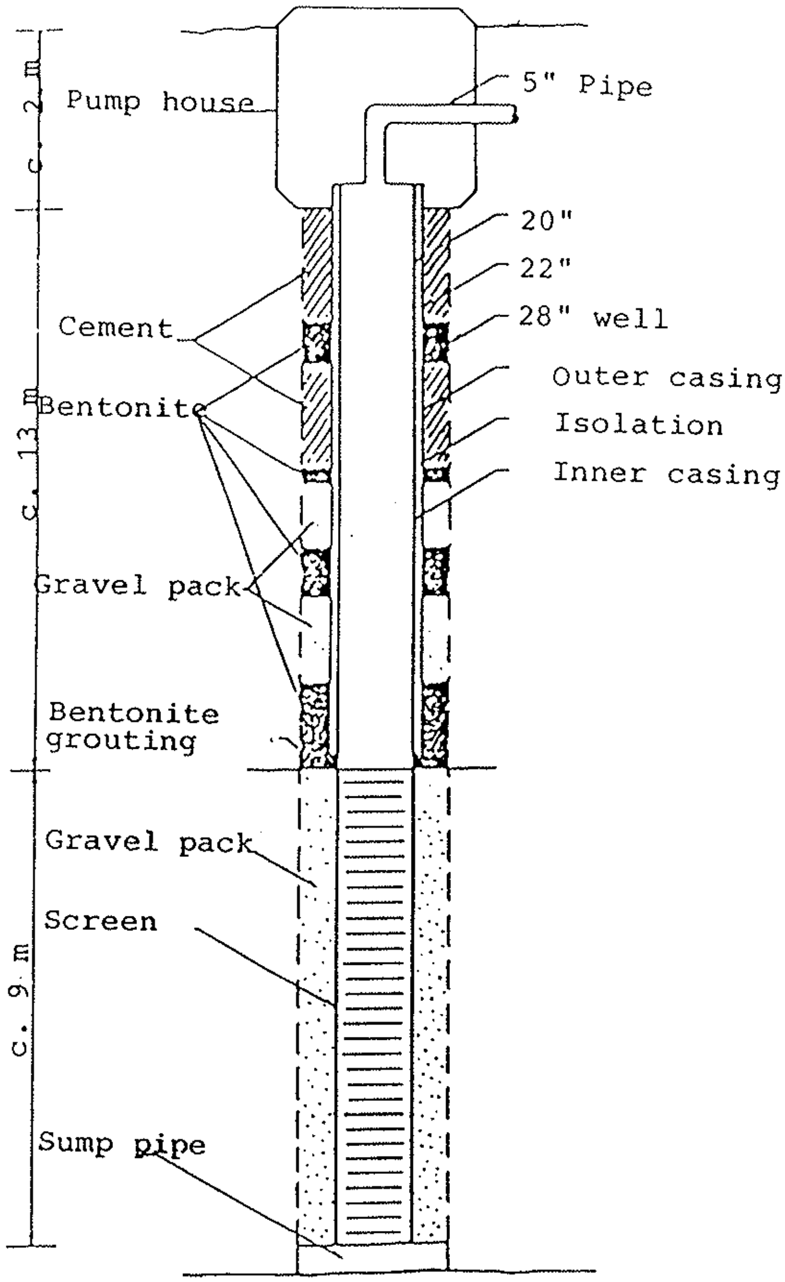


Fig. 7.2 Design of CW 2

stainless steel casing. The slots of the screen are 0.3 mm. The gravel pack is Lund no. 2. For the purpose of insulation, a steel pipe has been placed around the casing. The annulus between the casing and the steel pipe is filled with insulation foam.

7.1.2 Peripheral wells

The peripheral wells are, due to the higher permeability at the bottom of the aquifer, only screened at the lower 5 m of the wells. Apart from that, the peripheral wells only differ from the central well CW1 by their dimensions.

A diagram of the peripheral wells is shown in Fig. 7.3. The wells are about 25 m deep with a diameter of 8". The screen is 6" and a gravel pack around it is 2". A stainless steel casing and PVC insulation pipe continues from the top of the screen to the pump house floor as in the central well.

7.1.3 Auxiliary wells

In the storage area there is a natural groundwater flow, which has an influence on the temperature front in the store. Due to this, two auxiliary wells have been established.

The two auxiliary wells are placed on each side of the storage area, with a distance of 80 meters from the central well. The wells are equipped with 6-inch PVC-screens and -casings. They are connected to each other by a 3-inch buried PVC-pipe. The upstream well is equipped with a submersible pump, while the downstream well is prepared for injection of water from the upstream well.

The superstructure of the two auxiliary wells are circular wells with a diameter of 2,85 meters.

The wells are made of concrete. The cover of the wells are made of steel.

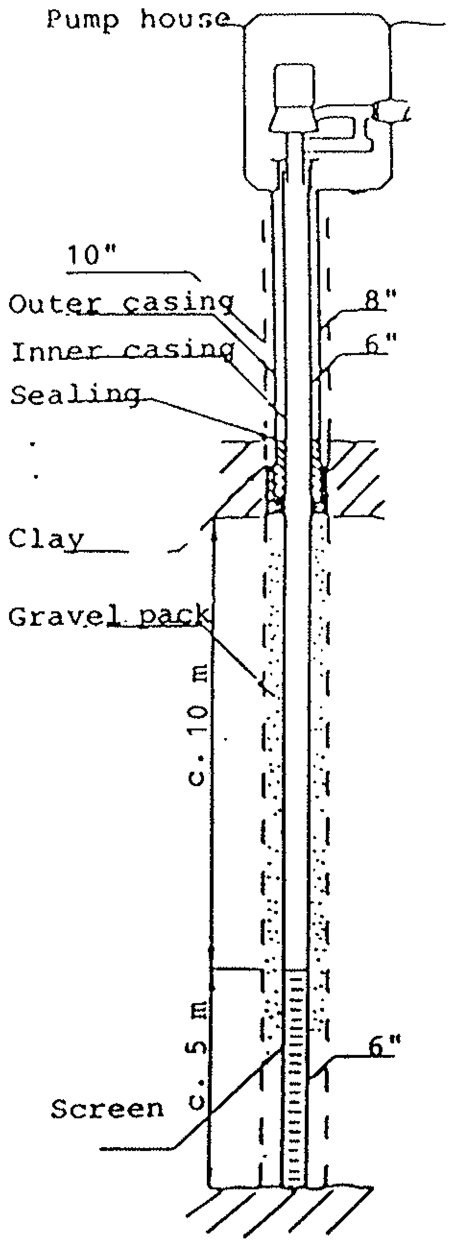


Fig. 7.3 Peripheral wells

7.1.4 Instrumentation wells

In the store a total of 17 instrumentation wells are situated. The location of these instrumentation wells is shown in Figure 7.4. Thirteen of these wells are drilled to the bottom of the

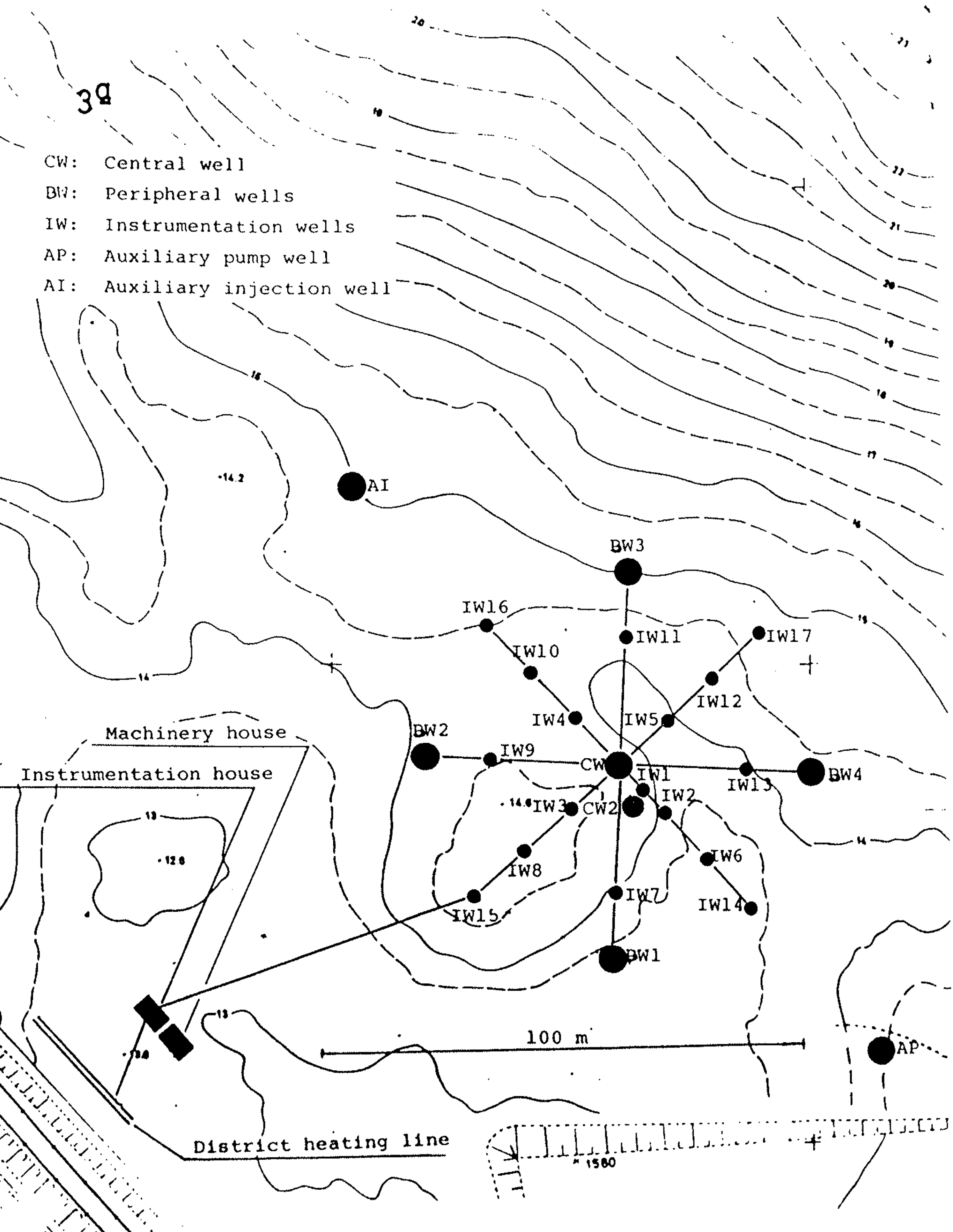


Fig. 7.4 Location of the instrumentation wells

reservoir (depth approximately 25 meters) and the four outermost wells are drilled to its middle (depth approximately 17 meters). The diameter of the wells is 8 inches. They are equipped at the bottom with copper tubes (ID 20 mm) for installation of temperature sensors. The four instrumentation wells IW1, IW2, IW6 and IW14 are furthermore equipped with copper tubes for installation of water level sensors. After placement of the tubes, the wells are filled with sand. The boreholes run into closed wells.

The leak through the upper confining bed appeared near the instrumentation well IW12 and an attempt to close the leak was made by injection of concrete in IW12. Therefore, today IW12 is out of function.

7.2 Pump stations

7.2.1 Central wells

The central well, CW1

The plant was established in 1982 with only one central well, CW1. This well was established both for injection and production. Today it is only used for production.

The piping in the well is shown in Figure 7.5. The horizontal dotted line shows the water level.

The superstructure of CW1 is a circular prefabricated well with a maximum diameter of 2 meters. The height of the well is 2,3 meters. The bottom of the well is 2 meters below the surface of the ground. The well is made of polyester reinforced by fibre glass, Fig. 7.6.

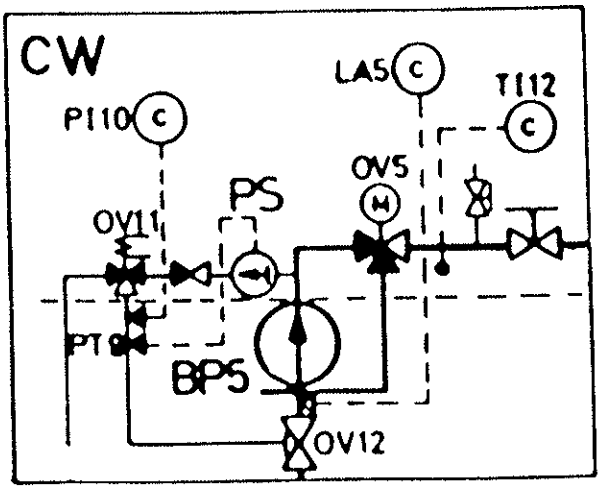


Fig. 7.5 Piping in the central well, CW 1.

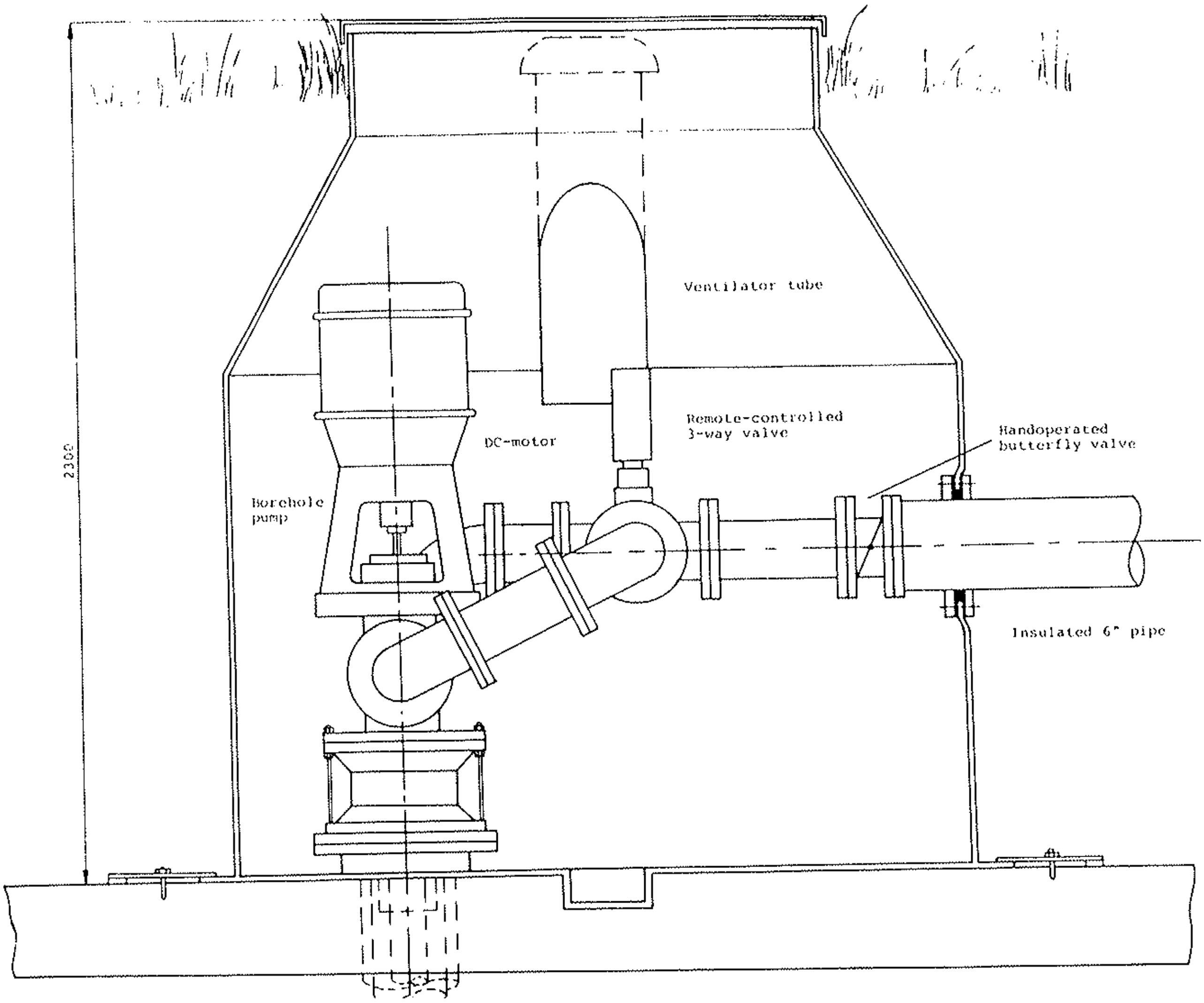


Fig. 7.6 Pump station, CW 1.

The well is provided with the following components:

BP5: Borehole pump, Grundfoss.

OV12: Sleeve valve operated by pressurised water. According to the mathematical model, injection of heat takes place over the entire height of the reservoir, while recovering heat takes place from the upper half alone. Therefore, a remotely controlled valve, which might close off the lower half of the well during heat recovery, has been installed. The valve has been placed as shown in Figure 7.7. A sleeve valve was selected, which is activated by pressurized water (the ground water itself, supplied from the borehole pump).

OV5: Motor-controlled three-way valve, Clorius. To effectuate change in operating mode, the flow is reversed by means of a motor-controlled three-way valve. During production the valve is set for straight through flow. During injection the valve is set for sidewards flow, whereby the flow is injected in CW2.

HV45: Hand-operated closing valve.

HV46: Automatic air-escape valve.

LA5: Computerized water-level sensor, H.F. Jensen.

TI12: Computerized temperature sensor.

The central well, CW2

This central well was established in 1985 after several leaks close to the old central well. It is used only for injection, while CW1 still is used for production (without problems).

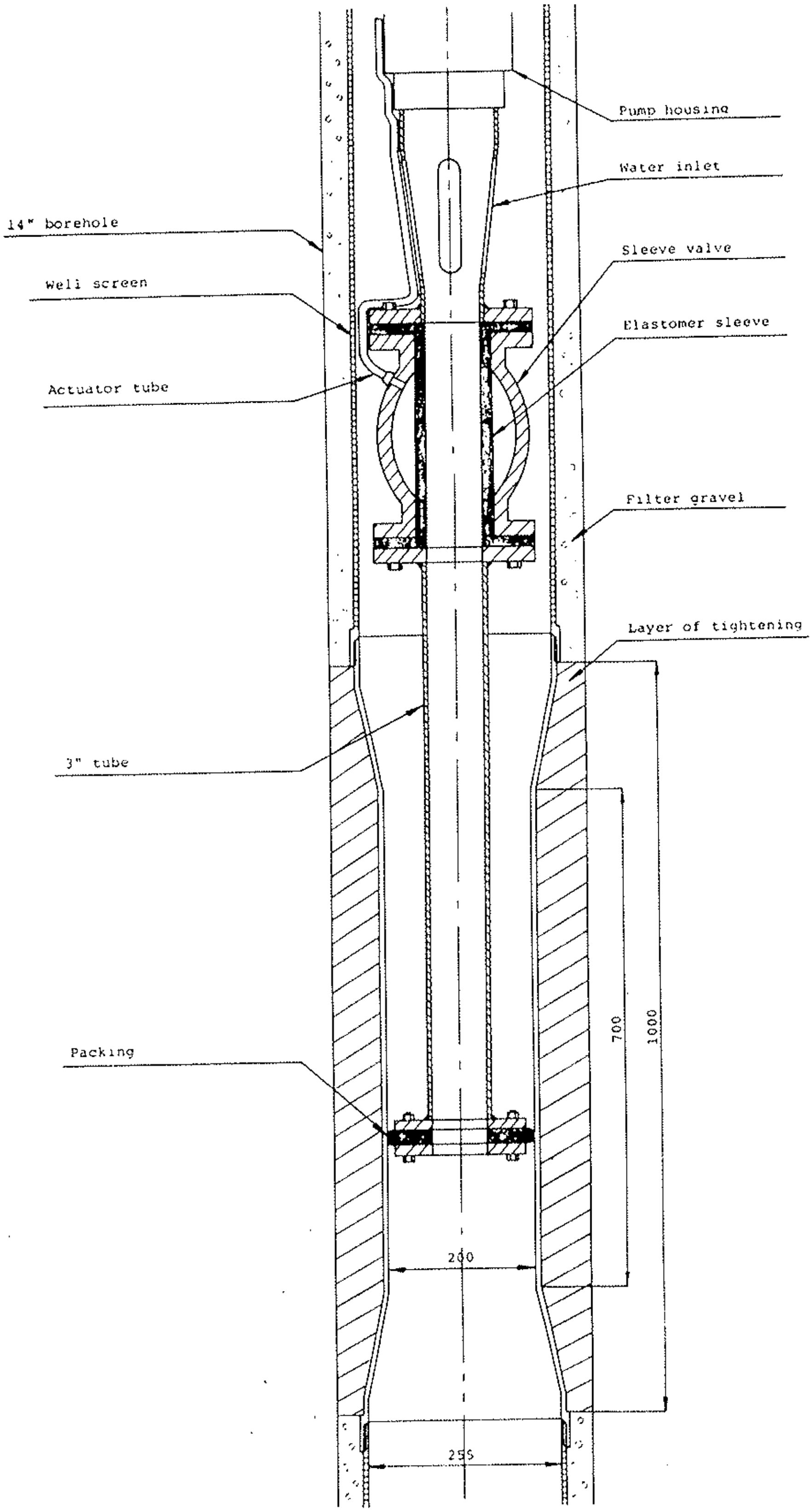


Fig. 7.7 Sleeve valve arrangement in CW 1.

The superstructure of CW2 is a circular well with a diameter of 2 meters. The height of the well is 2 meters, of which 1,8 meters is below ground. The well consists of 4 rings of concrete which are thickened by foam. The cover of the well is made of aluminium.

The 5-inch piping in the well proceeds 3 meters down in the drilling below the water level.

The following equipment is located in the well:

LA6: Computerized pressure transmitter, H.F. Jensen.

HV: Automatic air escape valve.

7.2.2 Peripheral wells

The four peripheral wells are all identical.

The piping in the peripheral wells is shown in Figure 7.8. The horizontal dotted line shows the water level.

The superstructure of BW1, BW2, BW3 and BW4 are like the one in CW1: A circular prefabricated well with a maximum diameter of 2 meters. The height of the wells is 2,3 meters, of which 2 meters are below ground. The wells are made of polyester reinforced by fibre glass, manufactured by Kemp & Lauritzen, Figure 7.9.

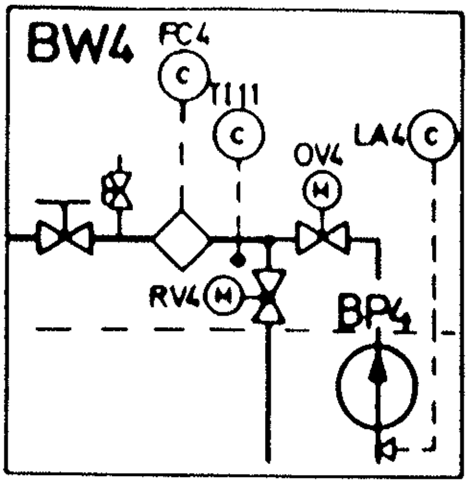


Fig. 7.8 Piping in the peripheral wells.

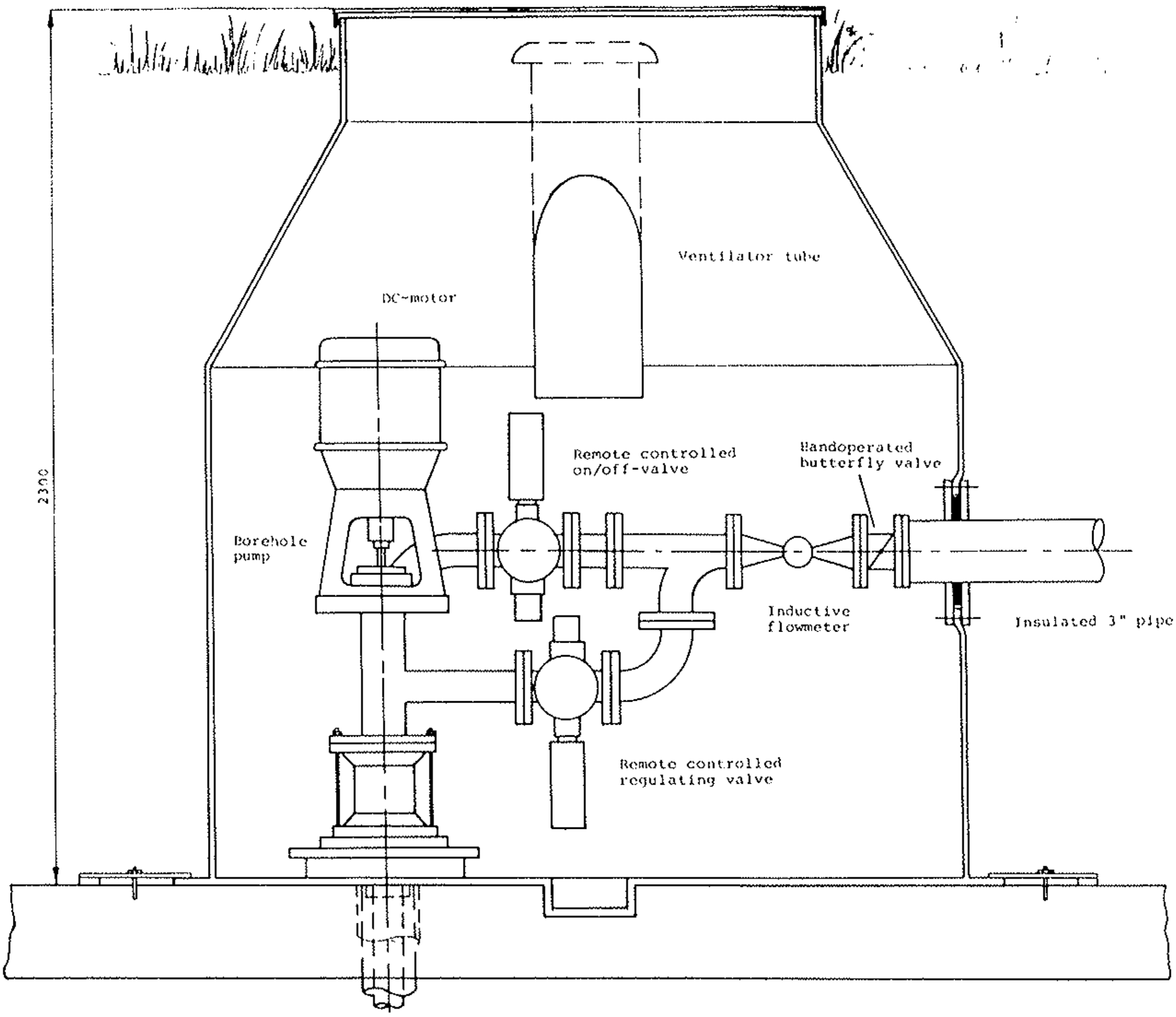


Fig. 7.9 Pump station, peripheral wells.

In the wells the following equipment is installed:

BP1, BP2, BP3, BP4: Borehole pumps, Grundfoss
In order to control the propagation of the temperature front, and to contribute compensation of the ground water flow, the flow is controlled from each of the peripheral wells independently. In addition, there is a demand for a variable total flow. For these reasons the borehole pumps are speed-controlled and equipped with thyristor-controlled DC-motors.

OV1, OV2, OV3, OV4: Motor-controlled two-way on/off valves, Clorius.

RV1, RV2, RV3, RV4: Motor-controlled two-way regulating valves, Clorius.
The reversal of the flow is accomplished by means of the two motor-controlled two-way valves: an on/off valve at the top of the riser and a regulating valve at the top of the injection tube. In this way it is possible to vary the flow to the injection tube.

HV41, HV42, HV43, HV44:
Hand-operated closing valves.

HV47, HV48, HV49, HV50:
Automatic air escape valves.

FC1, FC2, FC3, FC4: Flowmeters.

LA1, LA2, LA3, LA4: Computerized water-level sensors, H.F. Jensen.

TI8, TI9, TI10, TI11: Computerized temperative sensors.
V1, V2, V3, V4: Electric ventilators.

It has been necessary to install electric ventilators in the pump stations in order to protect the motors from thermal overload.

7.3 Pumps

7.3.1 Borehole pumps

The motors of the borehole pumps are above water and connected with long shafts to the runners that are located far below the water surface. This type of pump is chosen because of the elevated temperature of the water, which would make it difficult to cool the motor of an ordinary submersible pump. In order to control the propagation of the temperature front, and partially to compensate for the ground water flow, it is desirable to control the flow from each of the peripheral wells independently. In addition, there is a need for a variable total flow. For these reasons the borehole pumps are speed controlled, and they are equipped with thyristor-controlled DC-motors.

The pump capacities have been chosen on the basis of a maximum total flow of 80 m^3/h. Accordingly, the peripheral pumps are dimensioned for a maximum flow of 20 m^3/h each.

Central pump

The borehole pump is a centrifugal pump specially designed for heated water.

The pump capacity is 80 m^3/h with a water head of 34,8 m at 3100 rpm and a power of 15 hp. The central pump is a three-stage pump.

The pump is connected to the motor by a long 5-inch shaft.The long shaft consists of eight and one one-third sections of 600 mm, Figure 7.10.

At a temperature of 100^oC the minimum amount of pressure head required above the pump house is 3 meters of water.

The pump is driven by D.C. motor with a power of 21,0 kW at 3060 rpm.

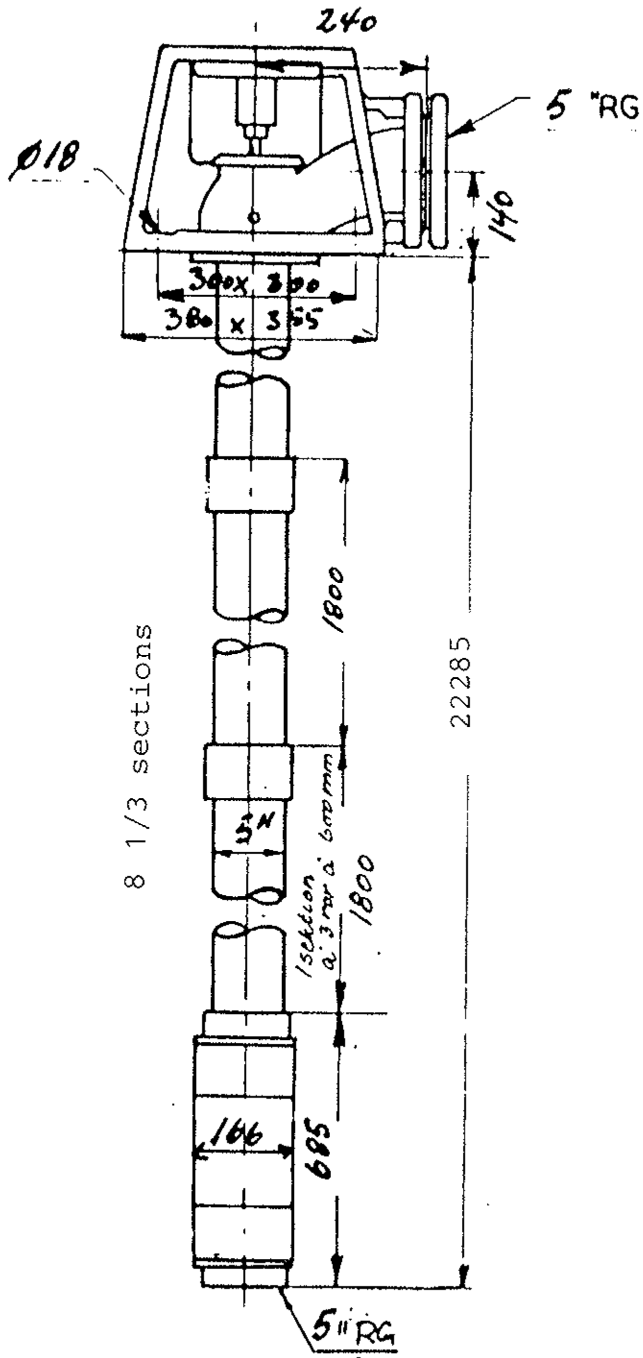


Fig. 7.10 Central pump.

The motor is controlled by a DC-thyristor placed in a box in the machinery house.

Peripheral pumps:

All the borehole pumps are centrifugal pumps specially designed for heated water.

The four peripheral pumps are all identical. The capacity of the pumps is 20 m^3/h with a water head of 35,8 m at 3300 rpm and a power of 4 hp. The peripheral pumps are four-stage pumps.

The pumps are connected to the motors by long 2,5-inch shafts. The long shafts consist of 8 sections of 600 mm, Figure 7.11.

At a temperature of 100^{o}C the minimum water head required above the pump houses is 3 m.

The motors driving the pumps are D.C. motors with a power of 4 kW at 3360 rpm.

The motors are controlled by DC-thyristor placed in boxes in the machinery house.

7.3.2 Booster pumps

Groundwater side

It has been decided to install a booster pump in order to reduce the size of the relatively expensive borehole pumps.

The booster pump is speed-controlled by means of a thyristor unit.

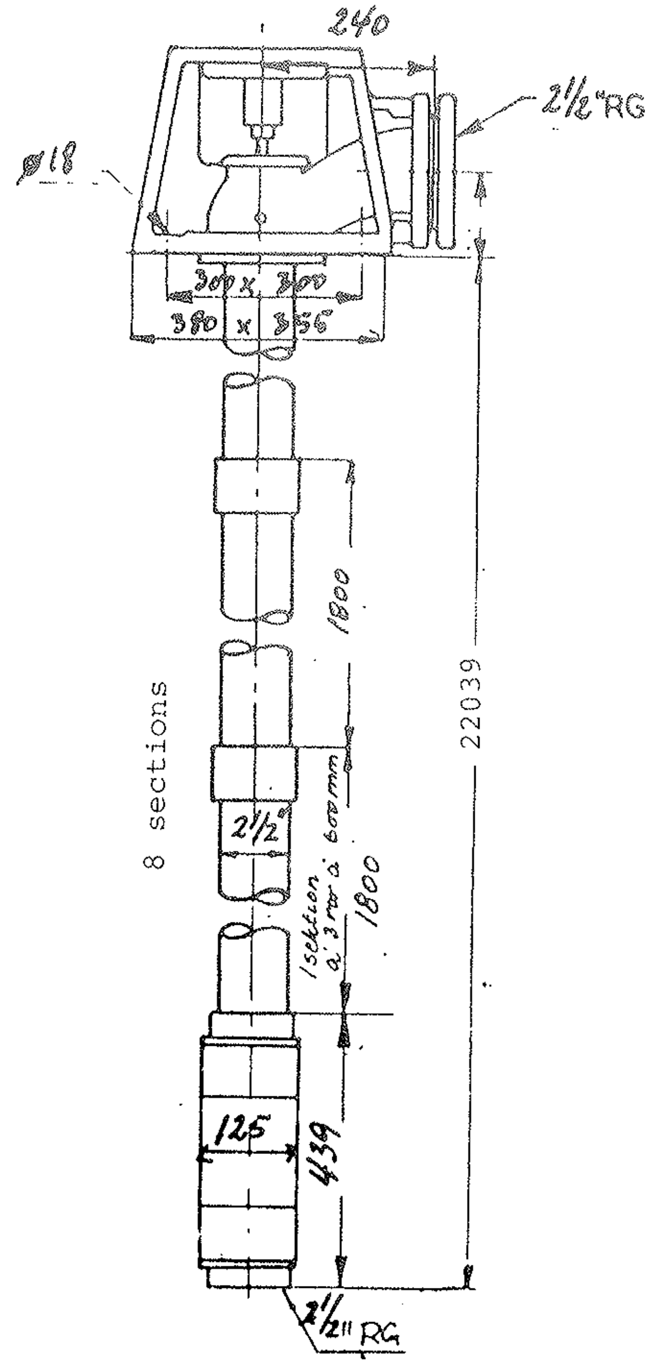


Fig. 7.11 Peripheral pumps.

In the following table the expected pressure drops in the system are presented (hot water):

	Pressure in bars	60 m^3/h	80 m^3/h
Borehole pumps	Elevation (max.) Pipe and valves, forward line	1.2 0.8	1.6 1.4
	Total	2.0	3.0
	Pipes and valves, return line	0.8	1.4
Booster pump	Filter unit Heat exchangers	1.0 1.0	1.8 1.8
	Total	2.8	5.0
Total pump pressure		4.8	8.0

The booster pump at the groundwater side is placed in the cellar in the machinery house behind the degasser.

The pump is a two-stage centrifugal pump with a capacity of 60 m^3/h at 4.5 bars and 2075 rpm.

The pump is equipped with a D.C. motor with a power of 21,5 kW at 2280 rpm. In order to protect the motor against thermal overload the motor has been equipped with an electric ventilator.

The motor is controlled by a DC-thyristor unit located in a box in the machinery house.

District heating side

A booster pump is needed on the district heating side in all modes of operation either to compensate for the pressure drop in the plant, or to increase the pressure to the level in the forward flow district heating pipe.

The pump is thyristor speed controlled.

The calculated pump pressures

Pressures in bars	Storing Summer	Delivery Autumn	Delivery Summer
	60 m^3/h	60 m^3/h	80 m^3/h
Pressure drop across heat exchangers etc.	2.0	2.0	3.6
Pressure drop from inlet to outlet of the district heating pipes	- 0.8	0	0.8
Pump pressure	1.2	2.0	4.4

The booster pump at the district heating side is a single-stage centrifugal pump with a capacity of 80 m^3/h at 4.5 bars and 3000 rpm.

The pump is equipped with a D.C. motor with a capacity of 21.0 kW at 3060 rpm. The motor is cooled by an electric ventilator in order to protect it against thermal overload.

The motor is controlled by a DC-thyristor unit placed in a box in the machinery house.

7.3.3 Auxiliary pump

A submerged pump is installed in the upstream auxiliary well. The flow variation is accomplished by pump speed frequency control.

The submerged pump is a centrifugal pump with a capacity of 10 m^3/h at 20 m head of water. The pump is equipped with a 1.1 kW motor. The diameter of the pump is 95 mm.

The pump is controlled by a frequency converter placed in the well.

7.4 Valves

7.4.1. Electric valves

To be able to change the flow path when the mode of operation is changed, the plant is equipped with remote-control two- and three -way valves, OV 1 - OV 10.

Seated valves have been selected. The regulating valve is in principle closed tightly, as the flow leaking by a closed valve is claimed to be less than 0,5% of maximum flow. Nevertheless, after several years of operation the valves do not close tightly causing flow-control problems.

The valves are activated by electric valve motors which are installed at the spindle of the valve.

Electric two-way valves

The electric two-way valves OV 1 - OV 4 are installed in the four peripheral wells in order to avoid reversed flow of water through the borehole pumps.

Technical data:

Product	Clorius M2
Materials:	
- fittings, box	cast iron GG 25
- spindle	stainless steel
Pressure stage	Pn 16
Seat construction	double seated
Mode of operation	close by pressurized spindle
Size:	
- opening	50 mm
- weight	14,8 kg
- k_{vs}	39 m^3/h

(k_{vs} is the amount of water which flows through the valve at a pressure drop of 1 bar)

Actuator	Clorius V3 I

Electric three-way valves

The electric three-way valves OV 6 - OV 10 are installed in the machinery house. Furthermore one three-way valve, OV 5, is placed in the central well CW 1. They are all installed with the purpose of changing the flow path when the mode of operation is changed.

Technical data:

Product	Clorius B
Materials:	
- fittings, box	cast iron GG 25
- spindle	stainless steel
Pressure stage	Pn 10
Seat construction	2 single seats relieved on pressure
Mode of operation	gate 1-2 closed by pressurized spindle, gate 1-3 opened
Size:	
- opening	125 mm
- weight	78,5 kg
- k_{vs}	215 m^3/h
Actuator	Clorius V 3 I

The electric three-way valves have caused many problems during operation. The seats stick in one position, so it is impossible to move the seat by operating the spindle.

The electric three-way valves OV 8 and OV 9 have been removed and replaced by T-pipes. It is possible to operate the plant without these two valves.

7.4.2 Regulating valves

One control valve is placed in each of the four peripheral wells (RV1-RV4) in order to control the amount of water injected in each well. In this way, it is possible to control the propagation of the temperature front.

A control valve RV5 is placed in the district heating pipe in the machinery house ahead of the heat exchangers. This valve regulates the district heating flow entering the machinery house.

All the regulating valves are seated valves. The leak flow by closed valve is in principle less than 0,5% of maximum flow.

The valves are activated by an electric valve motor connected to the spindle of the valve. The electric valve motor for the valve regulating the district heating flow, RV 5, is equipped with a spring-return. This spring-return closes the valve in case of power failure. In case of power failure, the whole plant will shut down with the valves placed in their currant positions. But by means of the spring-return the valve controlling the district heating flow will close, thereby letting the district heating flow bypass the plant.

<u>Technical data:</u>

Product	Clorius M2
Materials:	
- fittings, box	cast iron GG 25
- spindle	stainless steel
Pressure stage	Pn 16
Seat construction	double seated
Mode of operation	closes by pressurized spindle

RV 1 - RV 4

Size:	
- opening	50 mm
- weight	14,8 kg
- k_{vs}	39 m^3/h
Actuator	Clorius V4 E

RV 5

Size:

- opening	100 mm
- weight	32 kg
- k_{vs}	175 m^3/h
Actuator	Clorius V4 G

7.4.3. Hand-operated valves

The plant is equipped with 52 hand-operated closing valves. The valve type has been selected according to the local need. The valves are listed in Table 7.1.

Table 7.1

	Type	Product	Placement	Function	Size: Opening	Size: Weight
HV 1	Slide valve	Schmieding 400 GGG Pn 10/16	Machinery house	Closing the district heating system	125 mm	43 kg
HV 2	"	"	– " –	– " –	125 mm	43 kg
HV 3	"	"	– " –	– " –	125 mm	43 kg
HV 4	"	"	– " –	Closing the booster pump PG	125 mm	43 kg
HV 5	"	"	– " –	– " –	100 mm	28 kg
HV 6	"	"	– " –	Closing the degasser	100 mm	28 kg
HV 7	"	"	– " –	Closing the water treat-ment plant	100 mm	28 kg
HV 8	"	"	– " –	Closing the cyclone	100 mm	28 kg
HV 9	"	"	– " –	Closing the heat exchangers	100 mm	28 kg
HV 10	"	"	– " –	– " –	100 mm	28 kg
HV 11	"	"	– " –	– " –	100 mm	28 kg
HV 12	"	"	– " –	– " –	100 mm	28 kg
HV 13	"	"	– " –	– " –	100 mm	28 kg
HV 14	"	"	– " –	– " –	100 mm	28 kg
HV 15	"	"	– " –	– " –	100 mm	28 kg
HV 16	"	"	– " –	– " –	100 mm	28 kg

Table 7.1

	Type	Product	Placement	Function	Size: Opening	Size: Weight
HV 17	Slide valve	Schmieding 400 GGG Pn 10/16	Machinery house	Closing pipe stubs	32 mm	5,6 kg
HV 18	"	"	– " –	– " –	32 mm	5,6 kg
HV 19	"	"	– " –	– " –	32 mm	5,6 kg
HV 20	"	"	– " –	– " –	32 mm	5,6 kg
HV 21	"	"	– " –	– " –	32 mm	5,6 kg
HV 22	"	"	– " –	– " –	32 mm	5,6 kg
HV 23	"	"	– " –	– " –	32 mm	5,6 kg
HV 24	"	"	– " –	– " –	32 mm	5,6 kg
HV 25	"	"	– " –	– " –	32 mm	5,6 kg
HV 26	"	"	– " –	– " –	32 mm	5,6 kg
HV 27	"	"	– " –	– " –	32 mm	5,6 kg
HV 28	"	"	– " –	– " –	32 mm	5,6 kg
HV 29	"	"	– " –	– " –	32 mm	5,6 kg
HV 30	"	"	– " –	– " –	32 mm	5,6 kg
HV 31	"	"	– " –	– " –	32 mm	5,6 kg
HV 32	Ball valve		Machinery house	Closing between cyclone and sedimentation tank	25 mm	
HV 33	Ball valve		Machinery house	Closing at the sedimentation tank	25 mm	

Table 7.1

	Type	Product	Placement	Function	Size Opening	Size Weight
HV 34	Ball valve		Machinery house	Closing return water from sedimentation tank	25 mm	
HV 35	Butter-fly	CN-Børma	Machinery house	Closing one of the cyclones	65 mm	
HV 36	Slide valve	Schmieding 400 GGG Pn 10/16	Machinery house	Bypassing groundwater to degasser	100 mm	28 kg
HV 37	Seated valve		Machinery house	Regulating false air input to vacuumpump	10 mm	
HV 38	Ball valve	I.C. Møller	Valve wells	Closing district heating system	150 mm	
HV 39	"	"	- " -	- " -	150 mm	
HV 40	"	"	- " -	- " -	150 mm	
HV 41	Butter-fly	DEMCO	BW 1	Closing pumping wells	80 mm	
HV 42	"	"	BW 2	- " -	80 mm	
HV 43	"	"	BW 3	- " -	80 mm	
HV 44	"	"	BW 4	- " -	80 mm	
HV 45	"	"	CW 1	- " -	150 mm	

Table 7.1

	Type	Product	Placement	Function	Size	
					Opening	Weight
HV 46	Seated valve	CN-BØrma	CW 1	Air-escape in pumping wells	1/2"	
HV 47	"	"	BW 1	– " –	1/2"	
HV 48	"	"	BW 2	– " –	1/2"	
HV 49	"	"	BW 3	– " –	1/2"	
HV 50	"	"	BW 4	– " –	1/2"	
HV 51	Ball valve	G.F.	Machinery house	Closing acid pump	15 mm	
HV 52	"	"	– " –	– " –	15 mm	

7.5 Groundwater treatment plant

Environmental codes prohibit chemicals from being added to the groundwater. Therefore, it would not be possible to treat the water in traditional ways in order to avoid problems with deposits.

A problem of calcium carbonate precipitation was expected during the heating of the groundwater. This precipitation might cause scaling in the heat exchangers and clogging of the wells. Therefore, a water treatment plant was installed in which hydrochloric acid interferes with the hydrocarbonate equilibrium and causes a release of carbondioxide without precipitation of calcium. In addition, it is possible to clean the heat exchanger by chemical treatment, and a filtering unit has been installed downstream of the heat exchangers, in order to prevent precipitated material from clogging the wells.

The purpose of the water treatment plant is to remove carbon dioxide (CO_2) from the water ahead of the heat exchangers. The CO_2 must be removed from the water to avoid precipitation of the calcium carbonate ($CaCO_3$) in the heat exchangers. The CO_2 is present in the water as hydrogen carbonate ions (HCO_3). Hydrochloric acid is added to the incoming water. Free carbon dioxide is formed and it is removed in a degassing tower to avoid blockage of wells and pipes. The ion concentration of the ground water is unchanged. Hence, it was expected that the normally occurring destabilization of the layers of clay or a disingration of materials in the reservoir would be prevented. Nevertheless, the screen in the central well has blocked 3 times during injection. The blocking has all 3 times been caused by oxygen entering through leaks in the pipe system. The screen has each time been cleaned with a chemical agent for groundwaterwell cleaning. The chemical agent consists of a mixture of formic acid, phosphoric acid, hydrochloric acid, isopropyl alcohol and inhibitors.

The chemical reaction occurring when HCl is added to the groundwater is:

$$HCO_3^- + HCl \rightarrow CO_2 + H_2O + Cl^-$$

Figure 7.12 shows a schematic diagram of the water treatment plant. The water is mixed with concentrated hydrochloric acid. The acid is added through a membrane pump.

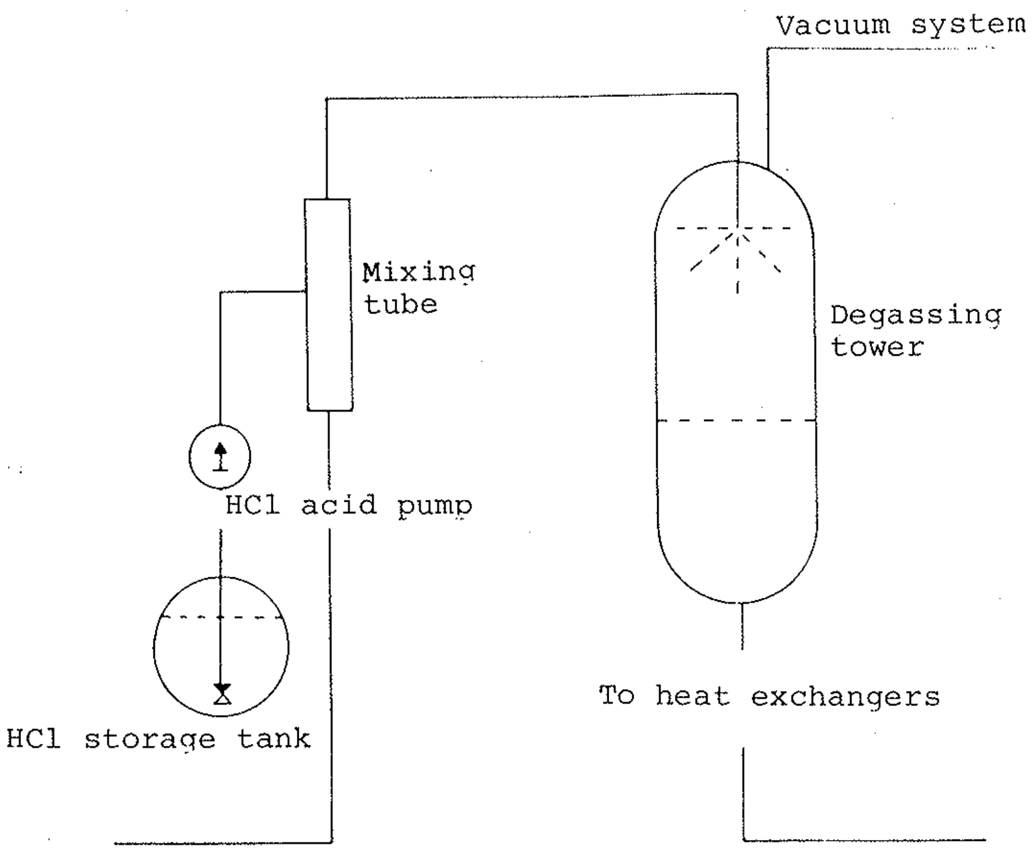


Fig. 7.12 Water treatment plant.

The pressure in the mixing tube is approximately 0.25 bar below atmospheric pressure due to the low pressure in the degassing tower. For this reason it has been necessary to install a counter valve to increase the counter pressure on the acid pump. If the pump had been allowed to work directly into the vacuum, the acid would have been sucked directly through the pump.

A fraction of the water/acid mixture passes through a chamber with a pH-electrode. The output from the pH-electrode is used to control the acid pump. The set point for the regulator is pH = 6. pH of untreated groundwater is 7.6. The control has not worked quite satisfactorily. There have been two reasons for that. Firstly, the response time of the pH-electrode is quite long and the signal fluctuates due to the turbulence of the water flow. Therefore, the controller has a tendency to oscillate. Secondly, the set point of the electrode changes with time and therefore there has been some periods where large amounts of acid have been added.

Due to these circumstances the acid pump today is controlled by the groundwater flow through the pipes and the pH-electrode is only used to check the amount of acid added. After this change, the water treatment plant has worked satisfactorily.

The acid/water mixture is passed through a degassing tower filled with pall-rings where the carbon dioxide is removed by a vacuum pump. The degassed water is then pumped through the heat exchangers.

Before the water from the heat exchangers is reinjected into the aquifer, it passes a filter which removes any suspended particles.

7.5.1 Acid system

The acid system is shown in Figure 7.13.

The acid storage tank is made from fibre glass reinforced plastic.

The groundwater level is quite high in the area. Therefore, the tank is covered with a 60 cm concrete plate to prevent the tank from being lifted up.

The acid passes through a PVC-tube to the acid pump. After the pump the acid passes a counter valve and is mixed with water in a mixing tube.

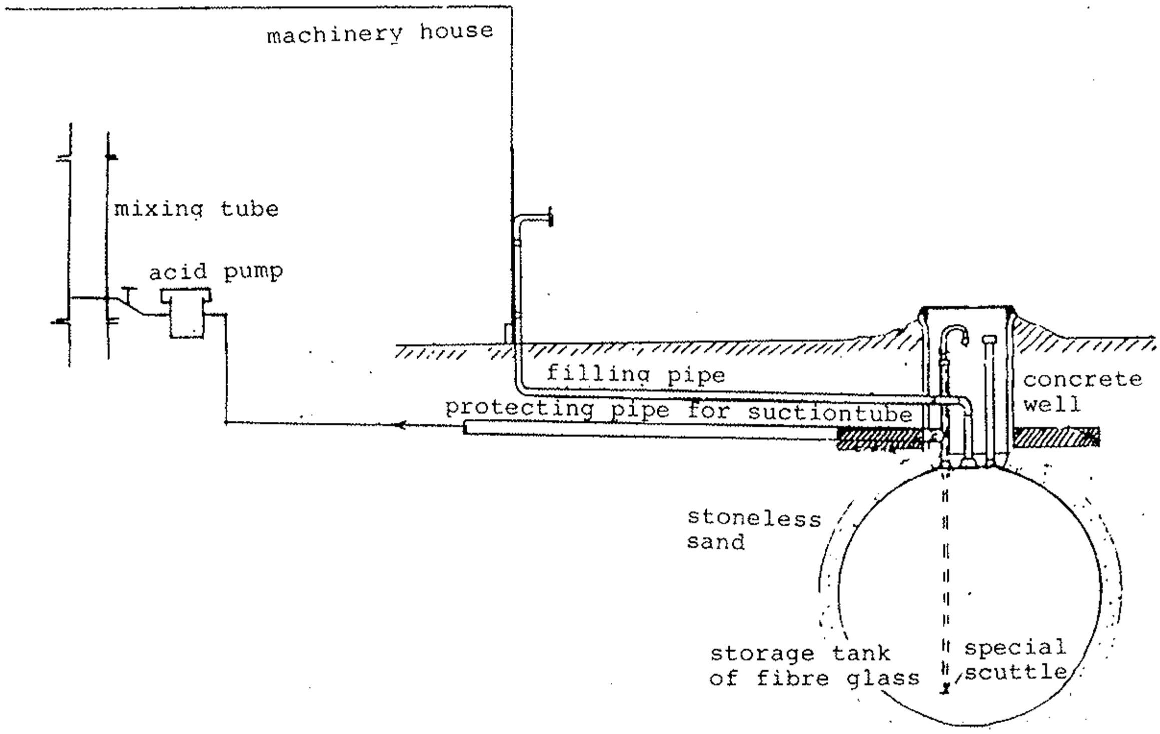


Fig. 7.13 Acid system.

Technical data

Acid system

Storage tank

Volume	:	5000 l
Material	:	Fibre glass reinforced vinylesther
Connections	:	Filling: 2"
		Suction: 2"
		Airation: 2"

Acid pump

Principle	:	Membrane pump
Product	:	Dosapro
Type	:	DMR 240
Max. capacity	:	at 120 stroke/min: 16 l/h
Max. pressure	:	15 bar

Controller unit

Principle	:	Frequency converter
Product	:	Danfoss
Type	:	VTL 1
Input signal	:	4-20 mA from pH-controller

Mixing tube

The concentrated acid is mixed with water in the mixing tube. The mixing tube is a stainless steel tube which is 1 m long and has a diameter of 100 mm. Perforated plates are placed in both ends of the mixing tube.

Degassing tower

The degassing tower is shown schematically in Figure 7.14.

Technical data:

Design pressure	:	1 bar
Design temperature	:	100^{o}C
Medium	:	Water with a content of acid and chloride
Filling	:	Pall-rings 25 x 25 mm

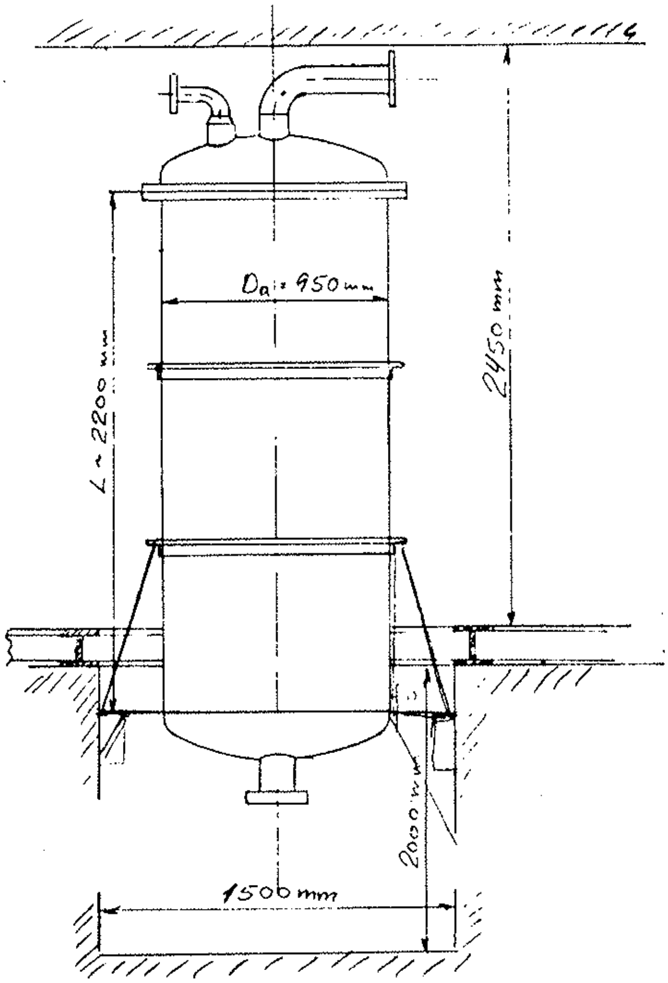


Fig. 7.14 Degassing tower

Inlet nozzle for water

Product	:	Spraying system Co.
Type	:	Distribojet 4R 95250
Pressure drop at 60 m^3/h	:	0,25 bar
Spraying angle at 60 m^3/h	:	65^o

7.5.2 Vacuum system

The vacuum system is connected to the top of the degassing tower in order to remove the free carbon dioxide formed in the low-pressure degassing tower.

The vacuum system consists of a vacuum pump, a unit for collecting any water present in the gas from the degassing tower and a safety valve (see Figure 7.15). The purpose of the safety valve and the water collecting unit is to prevent water from entering the vacuum pump. If the water rises above 1,6 meter in the degassing tower, the safety valve closes automatically. The water collector has a volume of approximately 5 l.

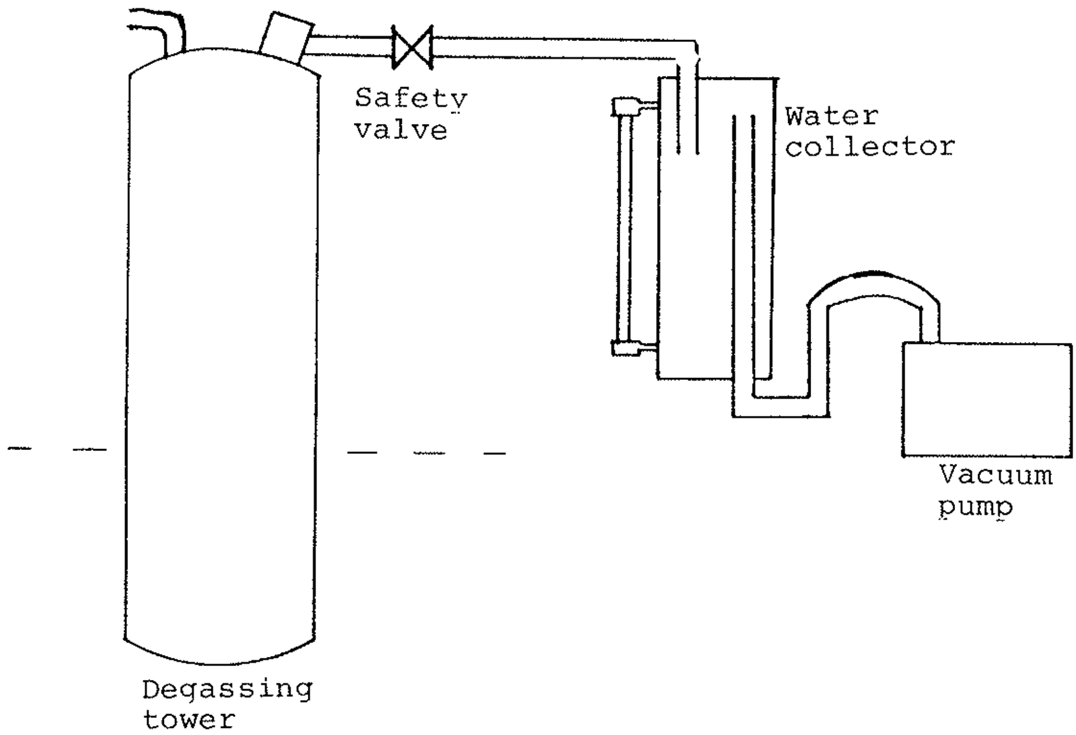


Fig. 7.15 Vacuum system

Technical data

Vacuum pump

Product	:	Leybold-Heraeus
Type	:	Varovac SI 60 F/C
Suction volume	:	160 m^3/h
Suction tube	:	25 mm steel tube with KF-connections
Discharge tube	:	25 mm PVC-tube connected to discharge tube through wall in the machinery house

7.6 Heat exchangers

To utilize to the maximum the relatively small difference between the forward- and return temperature of the district heating system, it is necessary to obtain as small a logarithmic mean temperature difference between the two media as possible. A value of $3^{o}C$ is expected. A temperature difference of this order could be accomplished in an economically reasonable way only by means of a plate heat exchanger. This type of heat exchangers has a large effective area per unit volume.

The material of the exchanger, as well as connection pipes and shut-off valves on the ground water side has been chosen to be acid resistant in order to permit chemical cleaning of scale deposits.

Two exchanger units are installed; this permits maintenance of the operation of the plant by one unit with the other out of service for cleaning.

Each of the exchangers is dimensioned for a flow of 30 m^3/h and a logarithmic mean temperature difference of $3^{o}C$ in the heat storing mode (with an assumed ground water input temperature of $63^{o}C$).

Technical data

Type	:	Plate heat exchangers
Product	:	Pasilac-Therm, 1050 RMGS
Plate quality	:	0.6 mm ASTM B 265
Sealing material	:	EPDM
Number of plates	:	161
Efficient heat transfer area	:	87,5 m^2
Heat transfer coefficient	:	4457 Kcal/h m^2 ^oC
Connections	:	100 mm standard

Due to fouling the heat exchangers have been cleaned once a year with HNO_3. Only a little fouling has been present. The first cleaning was made manuel by separating the heat exchanger and cleaning each plate, but cleaning by circulating HNO_3 in the heat exchangers seems to be quite as effective.

7.7 Filter

A filtering unit employing centrifugal separation has been used. It functions by means of water pressure itself. This system has the advantage of simplicity, and works unattended, with automatic removal of the slurry.

The filter unit is placed after the heat exchangers. It consists of two cyclone units. One of the units can be closed by a hand-operated valve. The cyclone units are cylindrical tubes with buckets to bring the water into rotation. The suspended particles move outwards and are collected in a sedimentation tank. The sedimentation tank is emptied manually. The unit is shown schematically in Figure 7.16.

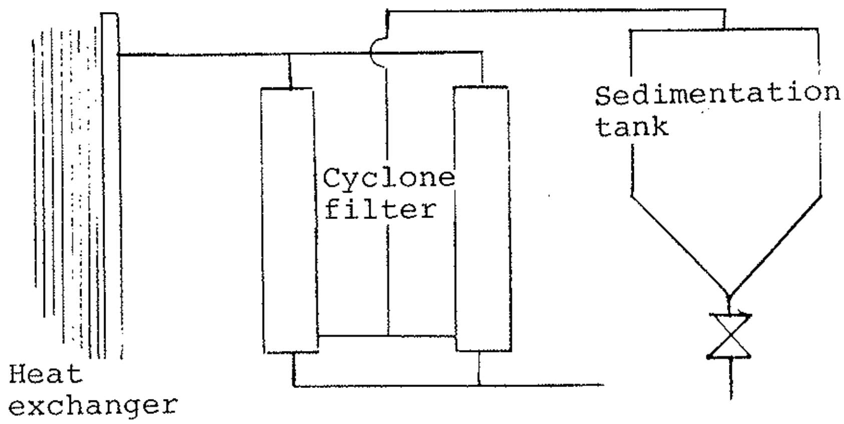


Fig. 7.16   Filter system

Technical data for cyclone filter:

Type	:	Hydrocyclone
Product	:	Dango & Dienenthal 2 SPR 30
Capacity	:	60 m^3/h, 1 bar
Minimum working pressure	:	1-2 bar
Maximum working pressure	:	10 bar
Suspended material flow	:	1% of water flow

By several years of operation it has appeared that the cyclone is only able to suspend relatively big particles, while smaller particles still pass the cyclone and settle in various components in the plant. The reason for this is apparently the working conditions of the cyclone. The cyclone is designed for a working pressure of minimum 1 bar, while the actual working pressure at this position in the plant is 0,5 bar at its maximum.

Due to these circumstances the cyclone and the sedimentation tank have been removed and replaced by a bag filter. The bag filter consists of four parallel units with a bag in each unit. The water enters the top of the filter unit, flows through the bag where suspended particles are collected, and exits at the bottom of the filter units. The filter bags are emptied manually. By emptying the bags once a week the plant operates without any sedimentation problems in the storage mode.

<u>Technical data for bag filter</u>

Type	:	Bag filter
Product	:	Silhorko
Capacity	:	60 m^3/h
Max. working pressure	:	6 bar
Net size	:	10 µ

8. CONNECTION TO DISTRICT HEATING SYSTEM

The storage plant has been connected to the district heating system by three pipes. One pipe has been connected to the forward flow line and two to the return line. The connection to the district heating system is shown in Figure 8.1.

During storage the forward flow line and one return line is used. During delivery in summer weekends the other return flow line and the forward line is used, while the two return lines are used during delivery in autumn/winter.

During autumn-delivery an unanticipated short circuit in the district heating return line has appeared. Due to the pressure conditions some of the heated return water reenters the heat exchangers from the district heating return line. In order to avoid this problem it would be necessary to insert a remotely controlled closing valve between the two pipes connecting the plant and the district heating return.

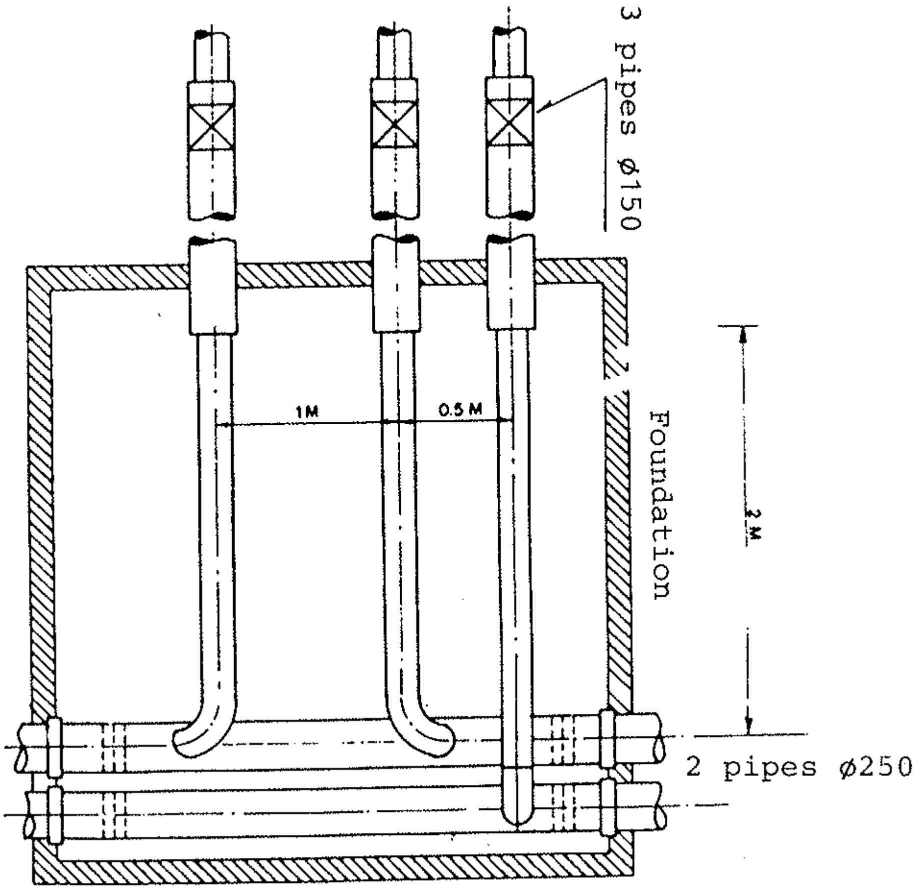


Fig. 8.1 Connection to district heating system

9. INSTRUMENTATION

The instrumentation wells are equipped with several temperature sensors distributed over the height of the reservoir. In 4 of the instrumentation wells also the water level is measured. Furthermore, the water level is measured in the 5 pumping wells.

In addition, temperature, pressure and flow are measured at various points in the pipes, and from this, other parameters such as transferred energy can be computed.

The instrumentation of the plant is shown in Figure 9.1. The pumping wells are equipped with pressure transducers, flowmeters and temperatures sensors. On each side of the heat exchangers temperature sensors and pressure transmitters are inserted.

The groundwater piping in the machinery house is equipped with a pressure-activated controller. This controller measures the injection pressure. At too high injection pressure the controller

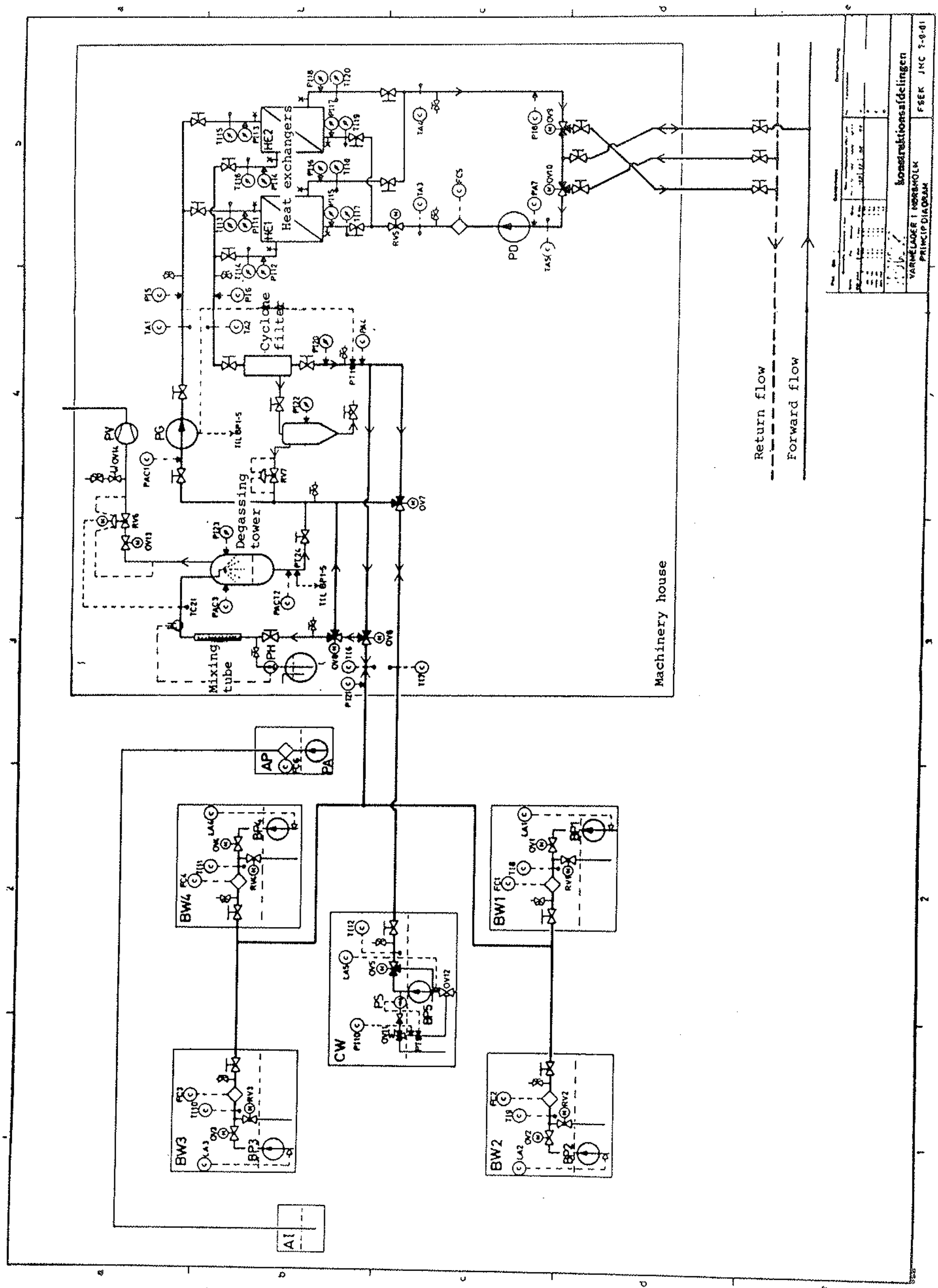


Fig. 9.1 Instrumentation of the plant

is activated and the plant shuts down. The injection-pressure controller has shown to be a very important element in the plant, and it has been shown to work satisfactorily.

The piping system both at the groundwater side and the district heating side are equipped with pressure transmitters and temperature sensors at various points. Furthermore, a flowmeter to control the incoming district heating flow has been installed at the district heating side. All these measuring devices are necessary to control the plant during operation.

9.1 Temperature measurements

Temperature measurements are currently made at several points of the aquifer formation by means of temperature sensors in the instrumentation wells.

Figure 9.2 shows the distribution of the wells in the storage area. The instrumentation wells are placed at four circles with respectively 1, 4, 8 and 4 wells per circle.

In circle 2, a well is equipped with 5 temperature sensors. In circle 3, a well is equipped with 9 temperature sensors, while a well in circle 4 is equipped with 1 temperature sensor.

Figure 9.3 shows a vertical cut of respectively a well equipped with 1 temperature sensor, 5 temperature sensors and 9 temperature sensors. The temperature sensors are installed with equal spacing between the two layers of clay.

Each of the wells have been equipped with watertight closed copper tube that is in direct contact with the reservoir. A steel wire, to which the sensors are fixed, is suspended in the tube (see Figure 9.4). The sensors are temperature-sensitive semiconductors. To prevent convection flows in the tube, disks made from a synthetic material have been attached to the wire at regular intervals. This measuring system has been tested in the laboratory and has proved accurate to within $\pm$ 1^{o}C.

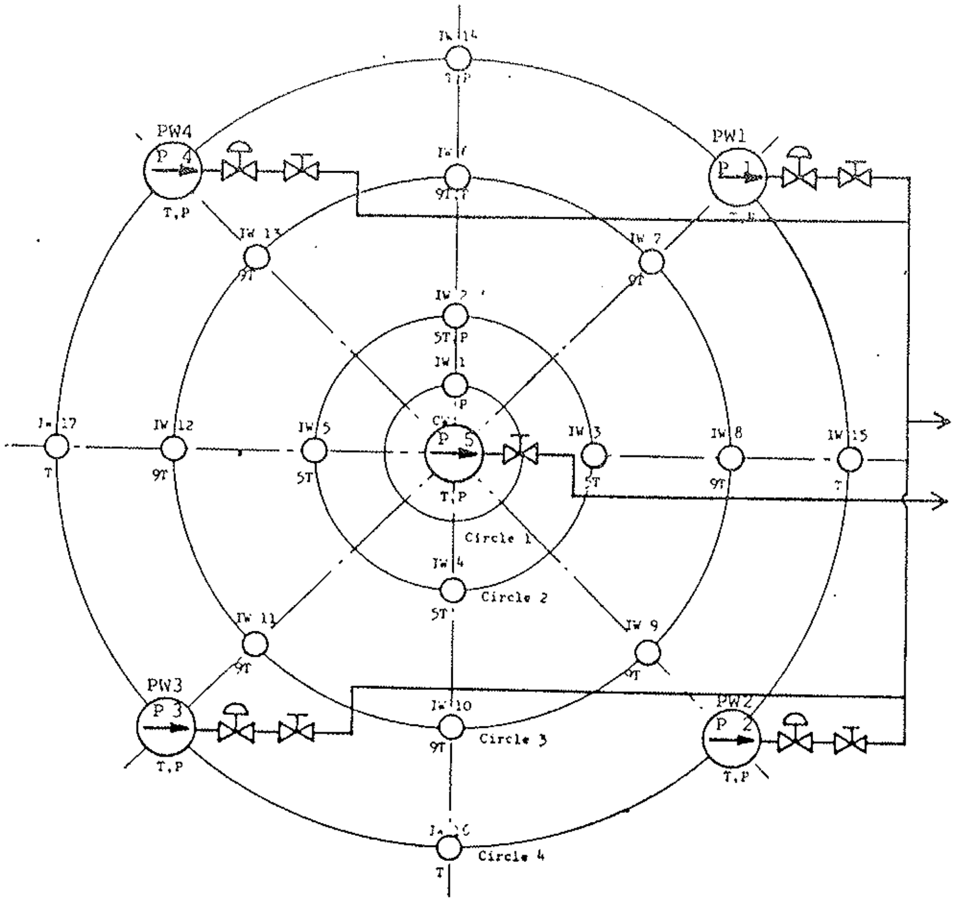


Fig. 9.2 Distribution of instrumentation in the instrumentation wells.

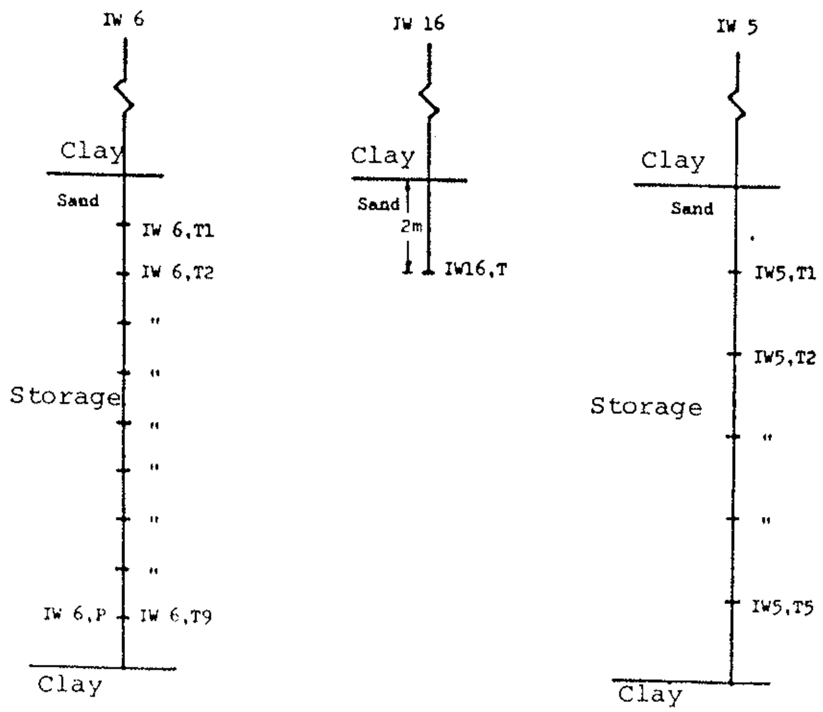


Fig. 9.3 Vertical plot of instrumentation wells.

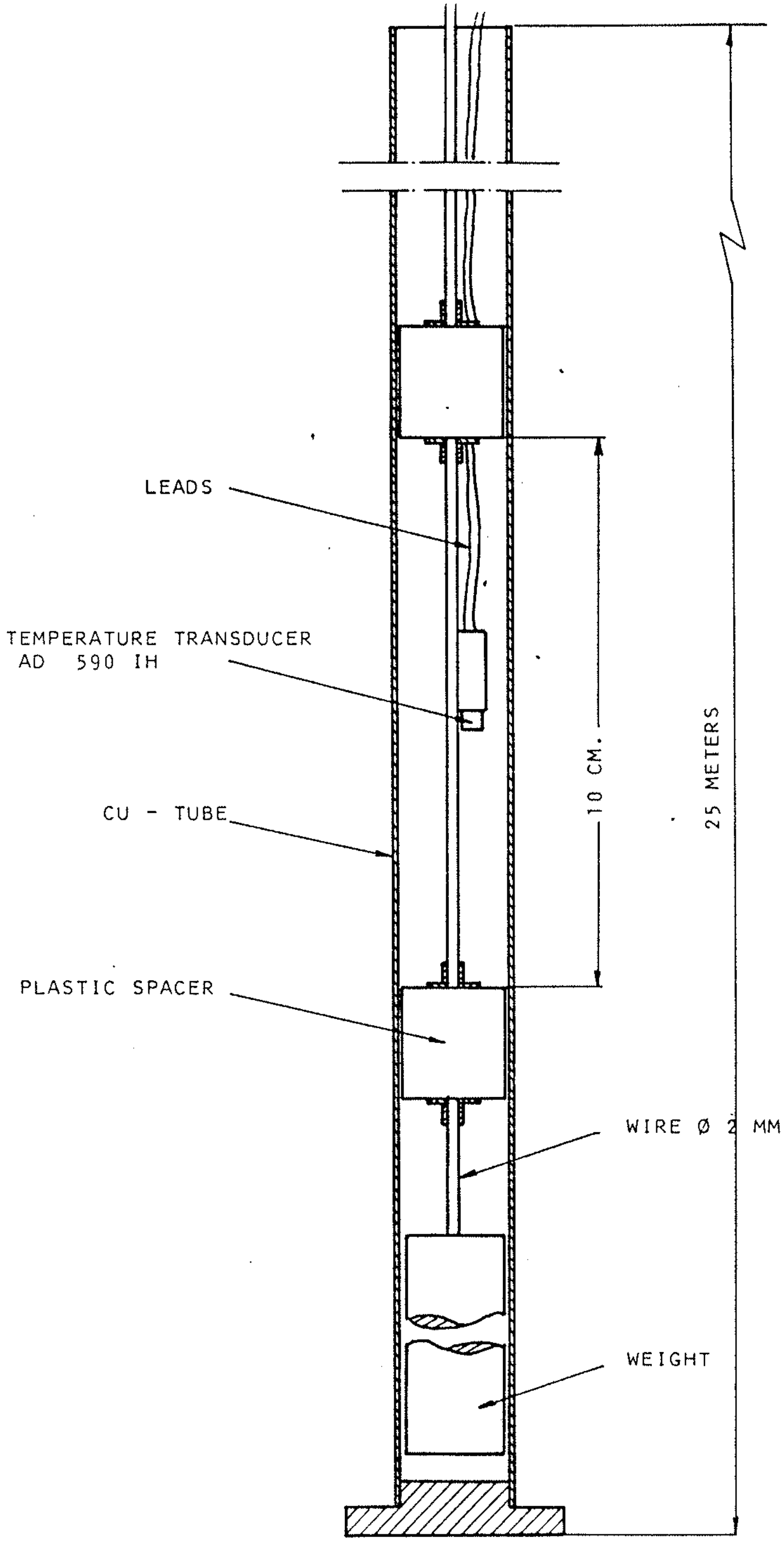


Fig. 9.4. Temperature measuring tube.

In the central well CW 1 and in the 4 peripheral wells 1 temperature sensor is installed below the borehole pump.

The positions of the temperature sensors installed in the piping system in the machinery house are shown in Figure 9.1. Beside the temperature sensors various pointer instruments for temperature readings have been inserted as shown in Figure 9.1.

During the quite extended construction period and subsequent length of operation with a number of interruptions, causing both unforeseen temperature and pressure variations, at times a significant number of the temperature sensors have been out of function, and it has been necessary to replace about half of the sensors with new sensors.

Technical data

Type	:	Temperature-sensitive semiconductor
Product	:	Analog Devices AD 590
Measuring signal	:	Current signal proportional with absolute temperature
Measuring resistance	:	10 000 Ω

9.2 Pressure measurements

In the central well and in the 4 peripheral wells pressure transducers have been mounted to record the water level. The pressure transducer is mounted below the borehole pump. Its reference is the pressure above the drilling pipe.

The 4 instrumentation wells IW 1, IW 2, IW 6 and IW 14 are also equipped with pressure transducers to record the water level variations in the storage area.

The chosen pressure transducer is a submerged level sensor. It has been unusually unreliable and therefore not satisfactory. The reasons for this are thought to be the high temperature, sudden variations in temperature and pressure, and vibrations due to the pumps.

Technical data

Type : Strain-gauge pressure transducer
Product : H.F. Jensen PA 2
Measuring signal: 4-20 mA

On the basis of these experiences a new system for pressure measuring has been developed for pressure measuring in the new central well CW 2. The system is shown in Figure 9.5.

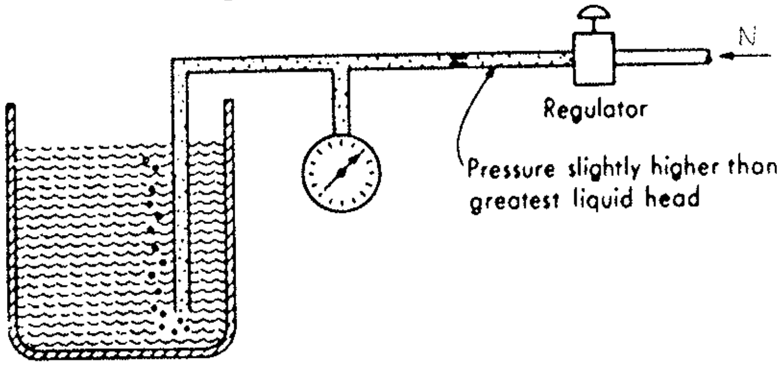


Fig. 9.5 Pressure measurement with nitrogen.

Nitrogen is injected in the top of the well below the water level through a thin copper pipe. The injected pressure of nitrogen necessary to displace the water up to water level is measured by the connected pressure transmitter.

A disadvantage of this system is that nitrogen has to be renewed every fourteen days, and if the nitrogen is exhausted, injection water will reach the pressure transducer and destroy it.

Technical data

Type : Pressure transmitter
Product : H.F. Jensen
Measuring signal: 4-20 mA

Figure 9.1 shows the various points at which pressure is measured in the piping system in the machinery house. Technical data and purpose of the various pressure transducers are listed in Table 9.1.

Table 9.1

Pressure transmitters

	Placement	Product	Measuring range bar above atm	Measuring signal mA	Measurement and/or purpose
PAC 1	Machinery house	Danfoss EMP 2	÷1....+1,5	4 - 20	Regulator of booster pump PG
PIT 2a	" "	" "	" "	"	Pressure measurement in top of degasser to KM relay
PIT 2b	" "	" "	" "	"	Pressure measurement in bottom of degasser to KM relay
P 2	" "	Signal from KM relay	0....+2,5	-10 -+10V	Difference pressure P2a-P2b from KM relay to regulator PG
PAC 3	Machinery house	Danfoss EMP 2	÷1....+1,5	4 - 20	Vacuum pressure at degasser
PA 4	" "	" "	0.....6	4 - 20	Injection pressure
PI 5	" "	" "	" "	"	Pressure after booster pump PG before heat exchangers
PI 6	" "	" "	" "	"	Pressure after heat exchangers before filter
PA 7	" "	" "	" "	"	Pressure at district heating flow entering the plant
PI 8	" "	" "	" "	"	Pressure at district heating flow leaving the plant

Table 9.1

Pressure transmitters

	Placement	Product	Measuring range bar above atm	Measuring signal mA	Measurement and/or purpose
PI 10	CW	Danfoss EMP 2	0..... 6	4 - 20	Pressure at sleeve valve
PI 21	Machinery house	"	0..... 6	4 - 20	Injection/Production pressure
PI 25	"	"	-1.....+1,5	4 - 20	Pressure before booster pump PG

Table 9.1

Pressure transmitters

	Placement	Product	Measuring range bar above atm		Measurement and/or purpose
P 2	Machinery house	Kamstrup Metro (KM) relay	0-25 mVS 0-25 mVS		Close valve to vacuum pump at too high water level in degasser
PT 9	CW	Diff. pressure pressostate SAUTER DFDC 7B58	0- 6 bar 0- 6 bar		Control pump PS on basis of pressure in sleeve valve
PT 19	Machinery house	Danfoss RT 110	0,2-3 bar 0,05-0,25 bar		Stop pumping at too high injection pressure
PT 24	Machinery house	Danfoss PT 200	0,2-6 bar 0,2-1,2 bar		Stop pumping at too high water level in degasser

Table 9.1

Manometers, pointer instruments

	Placement	Product	Measuring range bar above atm		Measurement and/or purpose
PI 11	Heat exchangers	Tempress 100 MSO-0	0-6		
PI 12	"	"	0-6		
PI 13	"	"	0-6		
PI 14	"	"	0-6		
PI 15	"	"	0-6		
PI 16	"	"	0-6		
PI 17	"	"	0-6		
PI 18	"	"	0-6		
PI 20	After cyclone	"	0-6		
PI 22	Sedimentation tank	"	0-6		

Table 9.1

Manometers, ponter instruments.

	Placement	Product	Measuring range bar above atm		
PI 23	Degasser	Tempress 100 M50-0	-1....+1,6		
PI 25	CW	Tempress 100 M60-0	0.... 8		
PI 26	Enter/exit mach. house, groundwater	Tempress 100 M50-0	-1....+6		
PI 27	Enter/exit mach. house, ground-water	Tempress 100 M50-0	-1....+6		

9.3 Flow measurements

In each of the 4 peripheral pumping wells, the flow rate in the two directions are measured. Furthermore, a flowmeter is mounted in the inlet pipe from the district heating system.

As flow rate detectors, magnetic flowmeters have been chosen.

Technical data, FC 1, FC 2, FC 3, FC 4

Type	:	Inductive magnetic flowmeter
Product	:	Mag-flux ndf-k NW 32
Placement	:	The 4 peripheral wells
Measuring range	:	0 +/- 20 m^3/h
Measuring signal	:	0-20 mA

Technical data, FC 5

Type	:	Inductive magnetic flowmeter
Product	:	Mag-flux ndf-k NW 80
Placement	:	Inlet pipe for district heating system
Measuring range	:	0-80 m^3/h
Measuring signal	:	0-20 mA

In the auxiliary pumping well a flowmeter, too, is placed to measure the flow rate in the auxiliary system.

Technical data

Type	:	Pressure difference over diaphgram
Product	:	NAF
Placement	:	Auxiliary pumping well
Measuring range	:	0-6.3 m^3/h
Measuring signal	:	0-50 mA

10. DATA ACQUISITION AND CONTROL SYSTEM

The data acquisition and control system is made up of regulators and of a computer system. The computer system consists of a local computer for data acquisition and controls placed in the instrumentation house at the storage plant and a medium-sized general host computer placed at Risø National Laboratory. These two computers are connected by two P&T modems and a permanently rented telephone line (Fig. 10.1). Furthermore, the local computer is connected to the district heating plant through three permanent telephone lines.

The tasks at the computers are distributed in the following way: The administrative control (management) of the storage plant is placed on the host computer. Storage of data is also handled here. Furthermore, processing and graphic output is handled by the host computer. Direct regulation of pumps and valves is handled by the local computer. The data acquisition of the measuring points in the storage plant is also handled by the local computer. Similarly signals from the district heating plant is collected there.

10.1 Host computer, RC8000

The medium-sized general computer placed at Risø National Laboratory is a RC8000 computer from "Regnecentralen A/S of 1979". The model is a 45 model with a up-to-date front-end computer. The disc system consists of a permanent disc of 10 M- bytes and a replaceable disc of 33 M-bytes. In connection with the RC8000 there is a 800/1600 bpi tape-station for standard computer tape.

RC8000 has several operative systems. Since many users have access to the machine, it is necessary to use a multi-user operative system. There is a batch operative system (BOSS) and an online operative system (mps TS). The total time a program can be in core in a multi-user operative system is 23,9999 hours. The programming languages for RC8000 is Fortran and Algol.

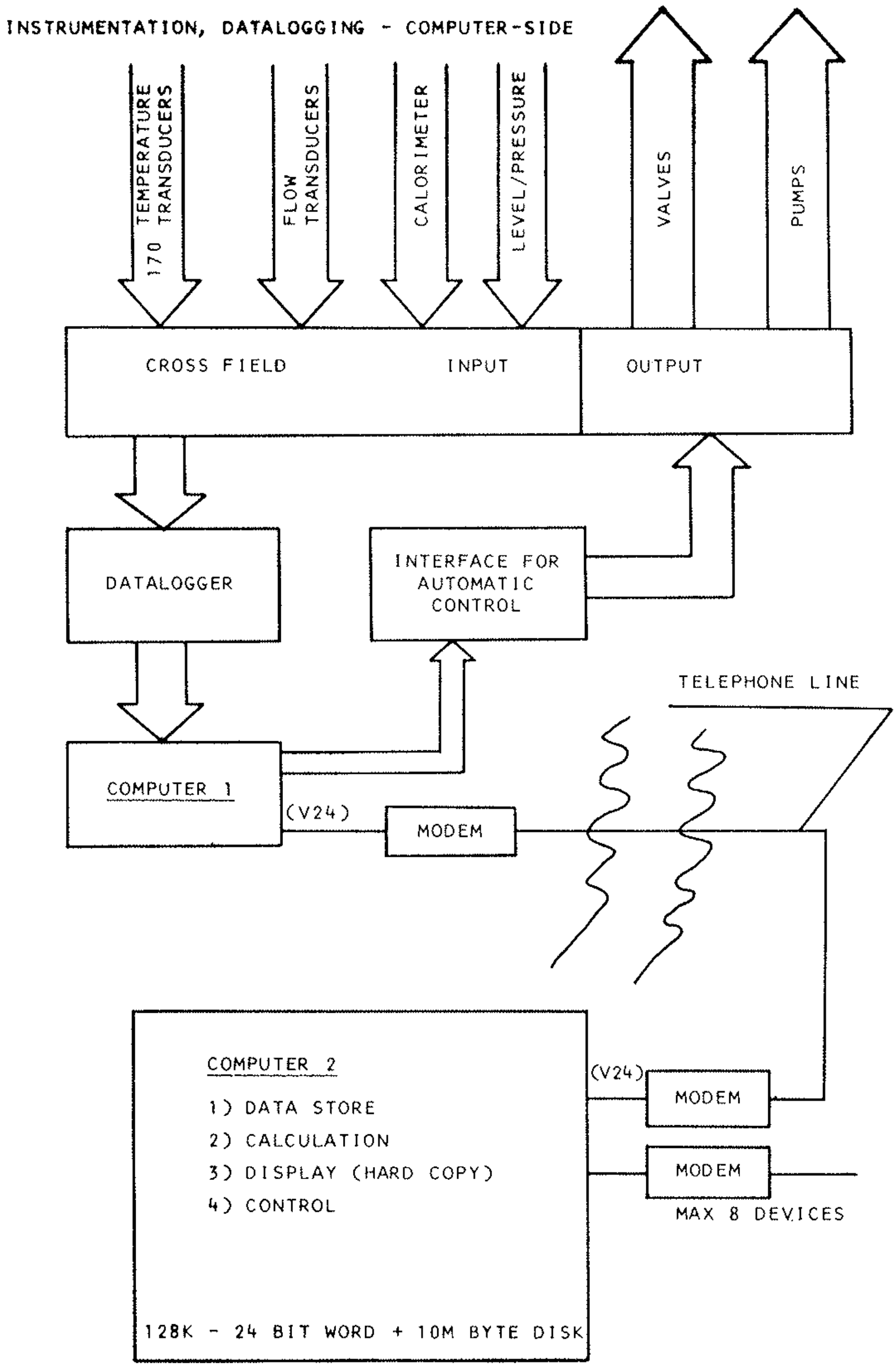


Fig. 10.1 Computer system.

10.2 Local computer, Macsym 2

The local computer placed in the instrumentation house at the storage plant is a Macsym 2 from Analog Devices. This computer has a storage capacity of 128 kbytes. The programming language is Mac-basic, a dialect of Basic, which among other things handles parallel processes. The computer is not equipped with a background storage, but a cassette station permits automatic restart of the system in case of power failure.

For data collection 224 analog input channels are installed, and for control and regulation of the plant 48 digital exits and 8 analog exits are available.

In main the local computer handles the following jobs:

* Establishment of communication with the host computer.

* Collection of measurements from energy storage plant, machinery house and signals from district heating plant, and the further transmission of data to host computer.

* Adjustment of valves and start/stop procedure of the pumps by order from the host computer.

* Regulation of pumps and regulating valves.

* Supervision of some very critical alarm settings.

* Display of the most important measurements.

* Generation of signal from district heating system concerning the instantaneous quantity of energy stored or delivered from the district heating side.

* Generation of watch dog signal.

Notes to some of the above-mentioned points

Establishment of communication with host computer

The local computer tries to establish the connection to the host computer. If the connection is unsuccessful, an error message is made at the display unit. If the communication is broken during an active operation of the plant, the local computer will shut down the plant after a certain time of lost communication.

Regulation of pumps and regulating valves

The five borehole pumps, the booster pump at the district heating side, the regulating valves placed in the four peripheral wells and the auxiliary pump are controlled by digital PID-regulators in the control program at the local computer. Furthermore, there is a possibility for both analog and digital control of the booster pump at the groundwater side. On the other hand, the acid pump is always regulated by an analog controller.

Set-points and amplification factors for the digital controllers are calculated at the host computer and are transmitted by the telephone line to the local computer.

The digital PID-regulators are equipped with max. and min. restriction of the output signal and it will inform the host computer if the restrictions are in constant operation.

Display of the most important measurements

The display program is used at the local computer for display of important measurements for operation of the storage plant. The display covers the following measurements:

* Groundwater flow F1 to F4 in percent of the total groundwater flow.

* The total groundwater flow F1 + F2 + F3 + F4 (m^3/h).

* District heating flow FC5 (m^3/h).

* Water level in the main wells (m H_2O).

* Water level in the aquifer in the four instrumentation wells IW1, IW2, IW6 and IW14 (m H_2O).

* Pressure in the pipe system: P25, P3, P4, P10 (bar), P2 (m H_2O).

* Temperatures in groundwater system: T1, T2 and temperatures in district heating system: T3, T4.

* The acidity in the groundwater, Ph.

* Actual amount of energy in groundwater system and district heating system (Gcal/h).

Furthermore, the time at which the measurements are collected is indicated.

10.3 Cooperation between local computer and host computer

Before starting the system, the user has to indicate the desired operating mode of the plant. This is done by using the users software. Hereafter all software in RC8000 is inactive.

The software in Macsym 2 consists of 3 main groups with auxiliary software:

* Regulation software

* Data acquisition software

* Transmission software

Initially when Macsym 2 is started the regulators are put out of function. Hardware protection measures prevent the on/off valves from changing position. Subsequently a scan of all input channels is made, and Macsym 2 starts the distribution program in RC8000. (The distribution program gathers data from the data acquisition program, whereafter the gathered datas are distributed to the updating program). At the end of the transmission, Macsym 2 starts the updating program, which sends data to Macsym 2. After receiving these data the on/off valves are activated. Also the regulators are activated if the data received from the updating program indicate the need for this.

When the positions of the on/off valves have been changed, the updating program demands a receipt from Macsym 2. The starting can only proceed when the valves are in the desired positions. Many cycles of data transmission between Macsym 2 and RC8000 may be required before starting is permitted.

The updating program communicates with some data files in RC8000. Files for user wishes and account files are files directly relating to the management. All other data files consists of data describing the function of the plant.

The updating program contains the primary regulators. These regulators adjust setpoints for the secondary regulators. By storage of a certain amount of energy it is not only one pump or one valve, which has to be regulated, but it is a total system of pumps and valves. The job for the primary regulators is to store or deliver a suitable amount of energy under constant control.

The distribution program communicates with the data acquisition files and the updating program. The size of the data acquisition file has to be adjusted in such a way that only the 10 Mega byte disc is needed. After acquisition of a certain amount of data the data are transmitted to tape.

11. MODES OF OPERATION FROM THE COMPUTER SYSTEM

It is possible to activate several modes of operation of the plant from the computer system:

* Standstill.

* Standby.

* Storage without water treatment.

* Storage with water treatment.

* Delivery, summer.

* Delivery, autumn.

Activation of a new mode of operation is effected by unlocking the valvelocks and the desired positions of valves are transmitted from RC 8000 to Macsym 2. When Macsym 2 has transmitted a new set of datas to RC 8000 these will be tested. If the valves are not in the desired positions, the updating program once more will transmit the desired positions of valves and signal the command to open the valveblock to Macsym 2. If all valves are in correct position, the set of data transmitted from RC 8000 will bring about the locking of the valvelock.

The correct position of the on/off valves in the different modes of operation is shown in Fig. 11.1.

12. DATA PROCESSING

A Fortran program has been developed for data processing. The program reads data from a measurement-data-file, which either is constantly updated or represents measurements from earlier periods. From these data, various parameters are calculated, so that the manager of the district heating plant and others who might be interested, occasionally can get an insight into the flow of energy from or to the reservoir. Furthermore, it is possible to read the signals from the temperature sensors in the reservoir. From these temperatures plots of isotherms can be made. The plots of isotherms can be made both in the horizontal

Fig. 11.1 Position of mechanical, non-manual components in different modes of operation.

		On/off valves													
		2-ways (2/2)				3- ways(3/2)							2-ways (2/2)		
Component		OV1	OV2	OV3	OV4	OV5	OV6	OV7	OV8	OV9	OV10	OV11	OV12	OV13	OV14
Placement		BW1	BW2	BW3	BW4	CW	Machinery house					CW	CW	Machinery house	
Acti-vation c: computer a: automatically		c	c	c	c	c	c	c	c	c	c	Indirectly c	c	c	c
Regu-lation c: computer a: automatically															
1. Standstill		0	0	0	0	1	0	0	1	1	0	1	1	0	0
2. Standby		0	0	0	0	1	0	0	1	1	0	1	1	0	0
3. Storage without water-treatment	active	1	1	1	1	0	1	1	1	0	1	1	1	0	0
	passive														
4. Storage with water-treatment	active	1	1	1	1	0	1	1	0	0	1	1	0	1	1
	passive												1	0	
5. Delivery, summer	active	0	0	0	0	1	0	0	1	1	0	0	0	0	0
	passive												1		
6. Delivery, autumn	active	0	0	0	0	1	0	0	1	0	0	0	0	0	0
	passive												1		

									Pumps											
Component		RV1	RV2	RV3	RV4	RV5	RV6	RV7	BP1	BP2	BP3	BP4	BP5	PG	PD	PA	PS	PH	PV
Placement		BW1	BW2	BW3	BW4	Machinery house			BW1	BW2	BW3	BW4	CW	Machinery house		AP	CW	Machinery house	
Acti-vation c: computer a: automatically									c	c	c	c	c	c	c	c	Indirectly c	c	c
Regu-lation c: computer a: automatically		c	c	c	c	c	a	a	c	c	c	c	c	a	c	c		a	
1. Standstill		0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
2. Standby		0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0
3. Storage without water-treatment	active	0	0	0	0	1/2	1	2	1	1	1	1	0	1	1	1	0	0	0
	passive					0			0	0	0	0	0	0	0	1	0/1	0	0
4. Storage with water-treatment	active	0	0	0	0	1/2	2	2	1	1	1	1	0	1	1	1	0/1	1	1
	passive					0			0	0	0	0	0	0	0	1	0/1	0	1
5. Delivery, summer	active	1/2	1/2	1/2	1/2	1/2	1	2	0	0	0	0	1	1	1	1	0/1	0	1
	passive					0			0	0	0	0	0	0	0	1	0/1	0	1
6. Delivery, autumn	active	1/2	1/2	1/2	1/2	1/2	1	2	0	0	0	0	1	1	1	1	0/1	0	0
	passive					0			0	0	0	0	0	0	0	1	0/1	0	0

Definitions

OV1–OV4: 0: closed valve; 1: open valve

OV5–OV11: 0: open sidewards; 1: straight through

OV12–OV14: 0: closed valve; 1: open valve

RV1–RV7: 0: passive, totally closed; 1: passive, totally open; 2: active, regulating

Pumps: 0: pump not in function; 1: pump in function and in the vertical directions allowing visual inspection of the state of the store. From this the situation may be evaluated and the desired changes may be determined. Hereby the regulation of the plant can be determined.

12.1 Accounting program.

For calculating to the district heating plant 4 accumulated datas are used:

* Total accumulated energy stored, ground waterside.

* Total accumulated energy stored, district heating side.

* Accumulated energy delivered during actual operation of the plant, groundwater side.

* Accumulated energy delivered during actual operation of the plant, district heating side.

These 4 accumulated data are introduced at the beginning and at the end of the accounting period. As the data to the account are calculated as differences between the items at two different times, it is also necessary to receive information about possible resetting of parameter references in the period of account.

12.2 Plotting program, horizontal plots.

Isothermal plots can be made from the temperature measurements in the reservoir.

A horizontal section is identified by its depth in percent of the depth of the aquifer measured from the bottom of the upper layer of clay. This definition has been chosen because of the irregularities in the limiting layers of clay in the storage area. The purpose of the plot is to visualize the propagation of the heated zone, so that an asymmetry caused by the variations in the velocity of propagation of the front can be compensated for by regulating the flow in the four peripheral wells.

In a given horizontal section the program interpolates linearly between the temperature signals in each instrumentation well. If the section is above or below the lowest sensor, the temperature is set to the value of the nearest sensor.

A network of radii and circles is constructed through the wells. Linear interpolations of the temperatures are performed along the resulting connecting lines.

The first ring of instrumentation wells consists only of the well (IW 1). The temperature from this is assumed to be symmetric around the central well for r = 7 m. IW 12 is out of function. The temperature here is therefore assumed to be a mean temperature of IW 11 and IW 13.

At r = 40 m there is only one temperature sensor in each of the four instrumentation wells. The temperature sensors are placed 2 m below the upper layer of clay. The temperature sensor in the four peripheral wells might indicate the temperature in the reservoir near the peripheral wells during operation of the plant. The temperature at the periphery of the store thus is determined alone from 8 temperature sensors. The isotherms in the range from r = 26,5 m to r = 40 m must, therefore, be treated with some caution.

In the above-mentioned network the temperatures at all the connecting lines are determined by this procedure, and each mesh is regarded as an element, where the temperature is found by interpolation. The principle, taken from the Finite Element theory, implies that the temperature in the element is determined by a second -order surface, determined by a number of points at the edge of the element. By traversing this surface the coordinates for the isotherms are found and the desired isotherms are plotted. An example of a horizontal plot in the reservoir is shown on Fig. 12.1.

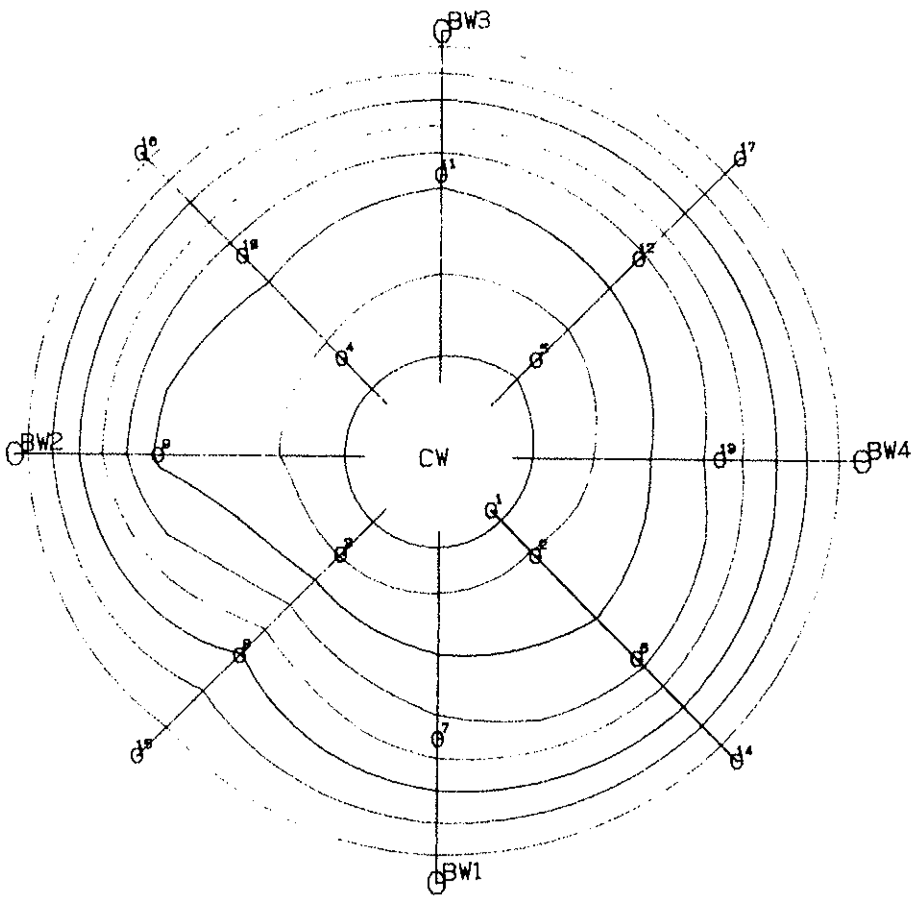
12.3 Vertical plots.

The user has the possibility to form a 3-dimensional picture of the temperature dispersion in the reservoir by definition of a section in arbitrary levels in the reservoir. Further details can be exposed by vertical sections.

The program is able to record isotherms in 8 sections along radii in the reservoir. These 8 sections go through the following wells (directions mentioned in 1):

1.	CW,	IW 1,	IW 2,	IW 6,	IW 14	(SØ)
2.	CW,			IW 7,	BW 1	(S)
3.	CW,		IW 3,	IW 8,	IW 15	(SV)
4.	CW,			IW 9,	BW 2	(V)
5.	CW,		IW 4,	IW 10,	IW 16	(NV)
6.	CW,			IW 11,	BW 3	(N)
7.	CW,		IW 5,	IW 12,	IW 17	(NØ)
8.	CW,			IW 13,	BW 4	(Ø)

Date : 86. 11. 5   Kl: 9. 3. 33 Layer of depth: 60%



Isotherms : 90 80 70 60 50 40 30 20

Fig. 12.1 Horizontal temperature plot.

All the vertical plots record isotherms in the interval from r = 7 m (IW 1) to r = 26,5 m (IW 6 - IW 13). The temperatures on the connecting lines of the wells are determined in the same way as for horizontal plots. As an example the isotherms in section 4 are based on the measurements in IW 1, mean temperatures of IW 3 and IW 4 in the 5 sensor levels, and measurements in IW 9.

The network in the vertical section is similar to the network in the horizontal section, where the temperatures at the edges of the elements are determined by linear interpolation between the recorded temperature. Thereafter, the coordinates of the isotherms at the quadratic temperature surfaces of the elements are calculated.

In the vertical sections one is able to read the levels and the extension of the reservoir in the actual section, as the limiting layers of clay are shown in the plots. The level of the upper limiting clay layer in the area varies between 13,85 m (IW 14) and 15,10 m (IW 15).

An example of a vertical plot is shown in Figure 12.2.

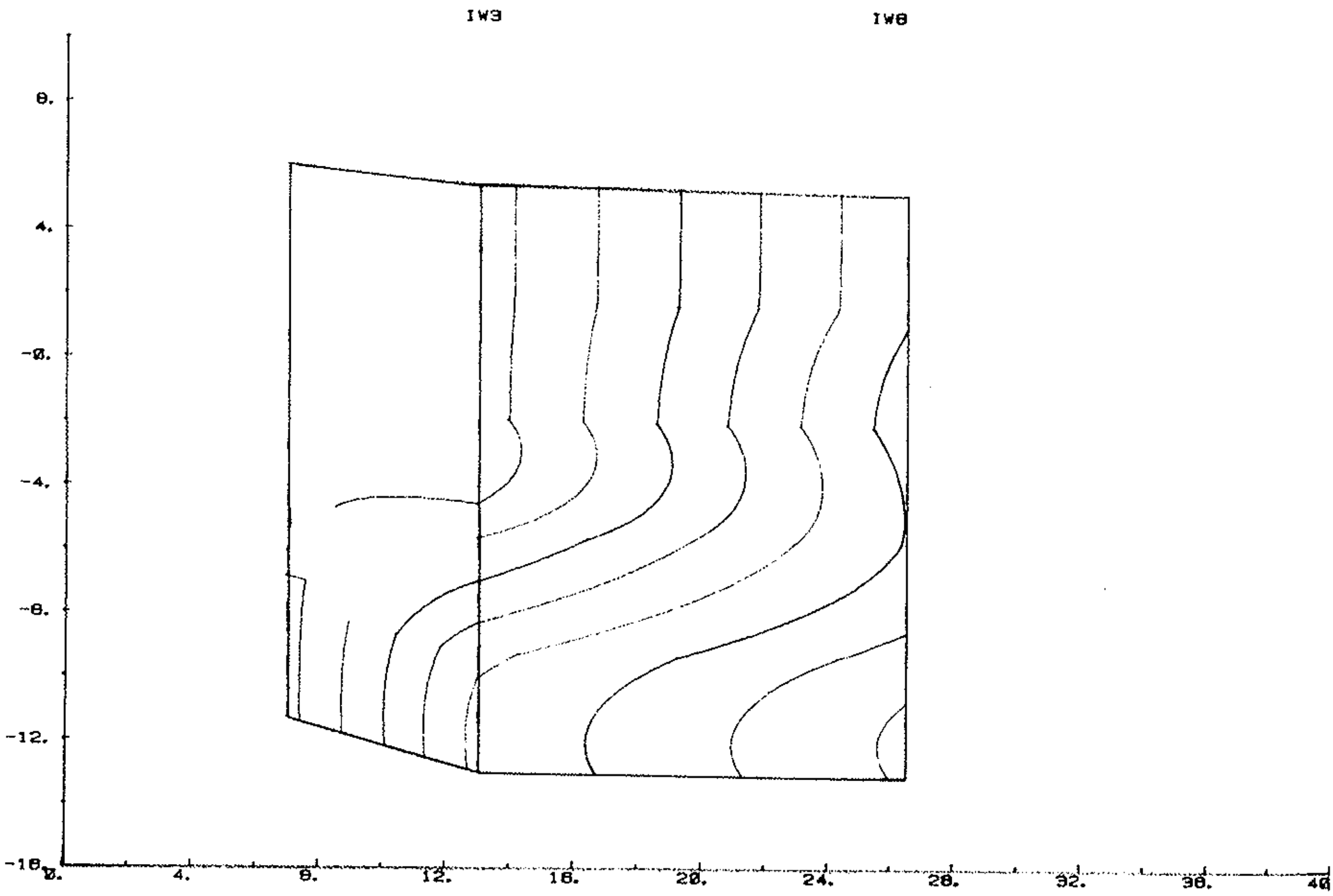
12.4 Relevant parameters as a function of time.

The above-mentioned horizontal and vertical plots reflect the dispersion of the temperatures in the reservoir at a certain time.

Beside this, it is possible to make plots of each parameter, which enters the data acquisition system, as a function of time. For example, it is often useful to monitor and record flows and injection pressure as functions of time during a night-time operation.

An example of a plot of flow as function of time is given in Figure 12.3.

Date : 86. 11. 5 Kl: 9. 3. 33



Isotherms : 90 80 70 60 50 40 30 20

Figure 12.2 Vertical temperature plot.

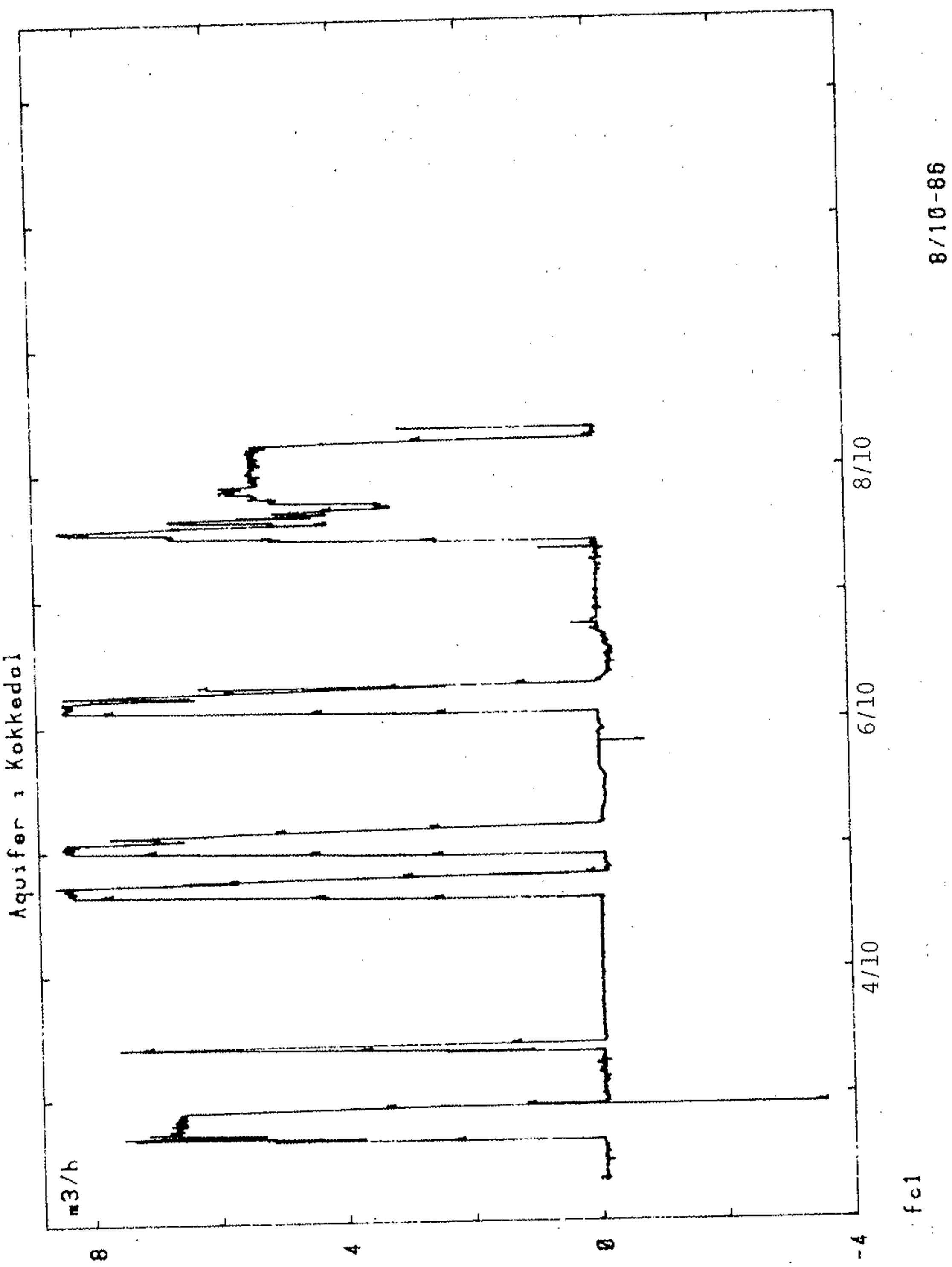


Fig. 12.3   Plot of flow as function of time

13. REORGANIZATION OF THE COMPUTER SYSTEM

The division of the computer system in two parts, with a local computer placed in the instrumentation room at the plant in Hørsholm and a RC 8000 computer placed at Risø, has been a source of problems. The RC 8000 system has caused troubles and the telephone line between Risø and the plant in Hørsholm too often has been out of order. Due to this, the plant has often been out of operation, not due to physical errors in the plant or the store, but due to communications break-down.

A rebuilding of the computer system has been made in 1986 to eliminate the problems caused by the telephone lines. The total computer system is now located at the plant.

The original Macsym 2 system placed in the instrumentation room at the plant has been extended to a Macsym 120 system by coupling a Macsym 200 box to a IBM PC/XT unit and a program packet.

By using a Macsym 120 system the existing measuring cards could be transferred directly from Macsym 2 to Macsym 120. This transfer has been done without dismounting the cables to the about 250 measuring channels. Another advantage by using a Macsym 120 system is that it was possible to transfer the original control system with only a few changes.

The control system for operation of the plant has been transferred from RC 8000 to Macsym 120. The Macsym 120 system takes care of the data acquisition and operational data. Data from the reservoir are stored temporarily on a 10 M byte harddisk.

2 data acquisitions are made:

1. Operational data.

2. Reservoir data.

Acquisition of operational data is made every 10 minutes. The operational data are data such as flow and pressure measurements in the wells and machinery house and temperature measurements for calculating the amounts of energy stored and delivered.

Acquisition of data from the reservoir is made every 2 hour. Reservoir data are the temperatures measured by the temperature sensors that are located in the reservoir.

The data stored on the hard disk are frequently transferred to floppy discs and transferred to Risø. Further processing of data such as vertical and horizontal plots thus is made possible.

A display and a keyboard is connected to the IBM PC unit and 300 Baud modems with a permanent telephone line are connected to Risø and the district heating plant.

At Risø and at the district heating plant terminals are connected to the system. Thus it is possible to operate the plant both from the district heating plant, from Risø, and from the storage plant. If the telephone lines to Risø or to the district heating plant are disconnected, the store will continue operation, as the control system now is located at the site.

A transfer of actual operational data and reports of alarms are made from Macsym 120 to the display at Risø and to the district heating plant. Difficulties of operation of the store are in this way quickly discovered.

The structure of the RC 8000 - Macsym 2 system, is shown in Fig. 13.1 while the structure of the Macsym 120 system is shown in Fig. 13.2.

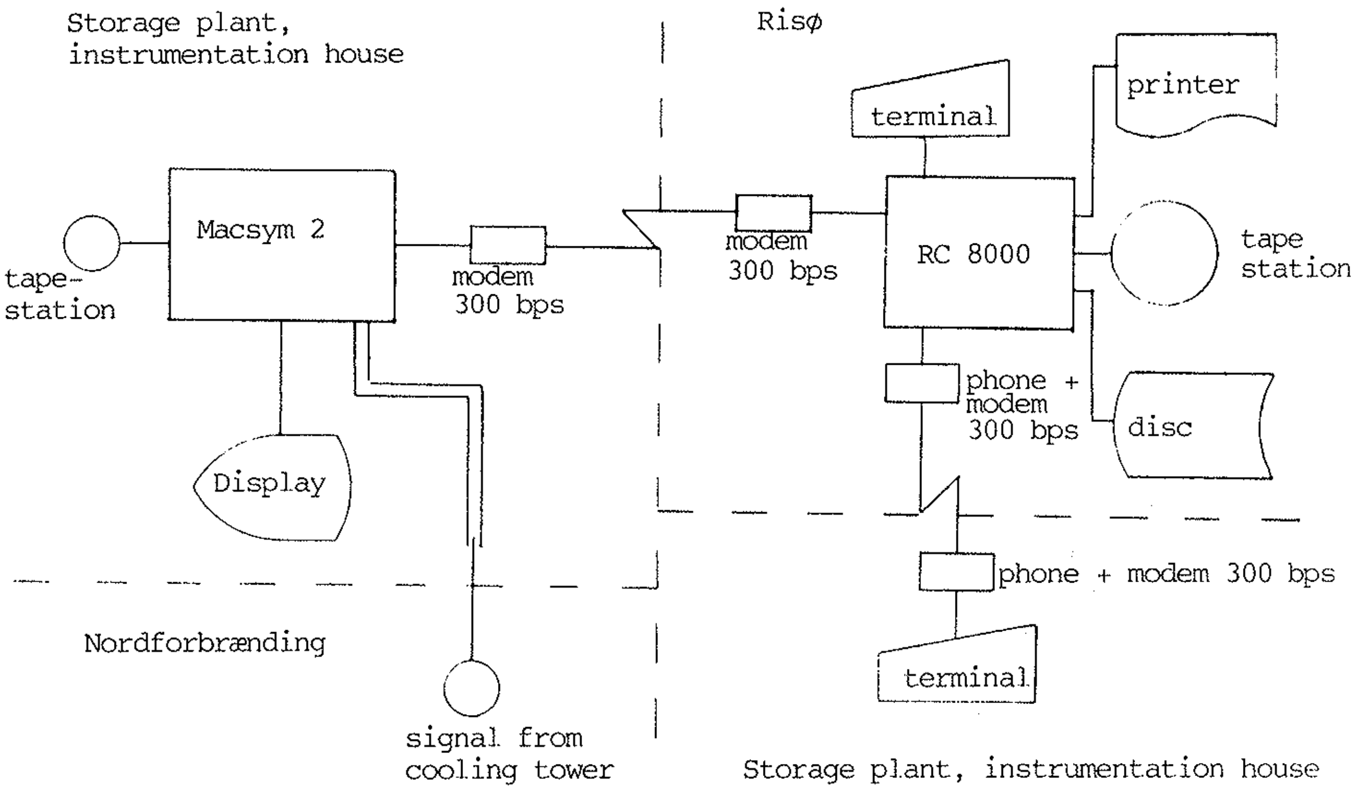


Fig. 13.1 RC8000 - Macsym 2 system

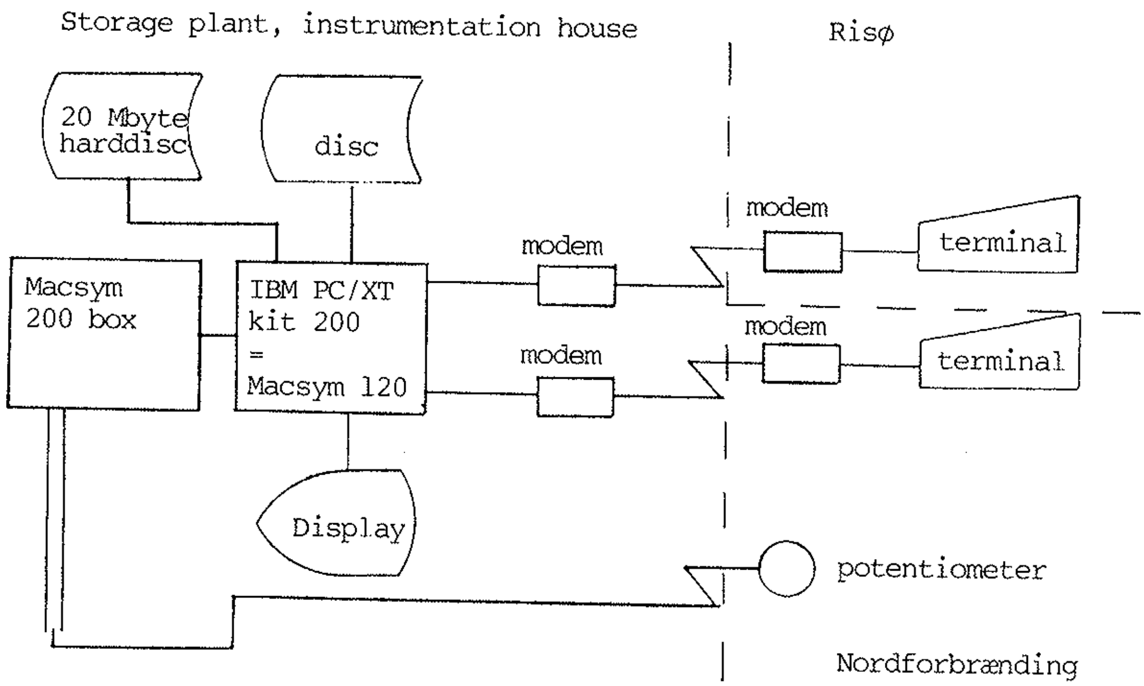


Fig. 13.2 Macsym 120 system.

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Abstract (Max. 2000 char.)

A part of the Danish aquifer thermal energy storage project consisted in construction of a demonstration plant. The demonstration plant was established in Hørsholm north of Copenhagen in 1982. During the years 1982-1987, altogether six charging processes have been carried out. Due to various difficulties in some years, the discharge (recovery) part of the storage cycle had to be omitted. In 1988 the demonstration plant has been closed down.

The project has been a collaboration between Risø National Laboratory, the Laboratory for Energetics at the Technical University of Denmark and the Geological Survey of Denmark.

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The present report describes the original construction of the plant. Also changes in the plant which have been made to improve the plant, are described.

The six storage-recovery cycles which have been carried out during the project will be described in a subsequent report. The experiences gained and the results will be discussed in this subsequent report.

Descriptors

AQUIFERS; COMPUTER CONTROL SYSTEMS; DEMONSTRATION PLANTS; DENMARK; DESIGN; DISTRICT HEATING; GEOLOGIC STRUCTURES; SEASONAL THERMAL ENERGY STORAGE; SITE CHARACTERIZATION; SPECIFICATIONS; THERMAL ENERGY STORAGE EQUIPMENT; UNDERGROUND STORAGE

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